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Landscape Consequences of Pennsylvanian Natural Gas Development
*Fragmentation effects of unconventional gas development upon the
future of Pennsylvania's old growth forests.*

Jeremiah Bernau

May 2013

Senior Thesis

Submitted in partial fulfillment of the requirements for the Bachelor of Arts degree
in Earth Science

Adviser, Kirsten Menking

Abstract

Pennsylvania's forests share a long and deep history that has been affected throughout the years by a number of external factors. The most recent threat to forest health is the development of unconventional shale gas production from the Marcellus Shale, which underlies much of Pennsylvania. Unconventional gas production has a large surface footprint as it is enabled by two key technologies—horizontal drilling and hydraulic fracturing. This study explores the effects of gas development upon forests that are part of a quarter-million hectare old-growth plan for the state of Pennsylvania. Because of severed mineral rights and State gas leases on State Forests, gas development poses an imminent threat to the future of Pennsylvania's old-growth forests.

By examining the effect of gas development in the region from 2008 to 2012, this study indicates the early stages of fragmentation in an increasingly segmented landscape. Landscape ecology was key in evaluating this area. Landscape metrics—specifically contagion, mean fractal index, percent forest cover, core forest, and total edge—were used to evaluate the study area. In addition to these data, extensive research into the effects of fragmentation and surface disturbance upon both long and short-term forest wellbeing was made. The study found that development increased edge length and the number of forest patches and decreased interior forest cover. It is recommended that no further leasing be allowed in these regions and that the forest management and regulation budget be increased through gas royalty payments and used to enhance the old growth characteristics of Pennsylvania's forest.

Acknowledgements

This project would not have been possible without the support and guidance of many people. Kirsten Menking provided support and assistance in editing this project, and never gave up on me when the deadlines inevitably passed. Nature Conservancy staff—specifically Nels Johnson and Tamara Gagnolet—were invaluable in both advising and providing data from which this project is created. James Whitacre of the Carnegie Museum shared the well permit data that this project was built around. Mary Ann Cunningham was indispensable in ending many an angry battle with ArcMAP; without her I would not have been able to process and create these data. I would like to thank Brian McAdoo for first suggesting this project, which has taken me places I could not have anticipated in the last 9 months. Finally, Steve Hamburg, the Chief Scientist at The Environmental Defense Fund, inspired me with the idea of forest fragmentation. This project would have been impossible without all of your support.

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Chapter 1: Thesis outline: Unconventional Gas, Forests, Future

The effect of natural gas resources from shale has sent reverberations throughout the energy industry (US EIA, 2012). Gas production has risen dramatically in the past decade because of technological innovations in horizontal drilling which, when paired with hydraulic fracturing, have enabled previously uneconomic gas resources such as the Marcellus shale to become economically exploitable. This energy source has shifted the principle electricity source in the United States away from coal and toward natural gas (Pratson et al. 2013). This thesis focuses upon the effects of the rapidly increasing amount of gas extraction upon forests in Pennsylvania.

Hydraulic fracturing has been widely criticized for its negative environmental effects (Arthur et al. 2009; Colborn et al. 2011). Criticism has focused largely on hydraulic fracturing's high water and chemical usage which has raised concerns of water and air pollution (Osborn et al. 2011). These issues eclipse the effects of surface disturbances from gas development and extraction in the media, yet surface disturbances may significantly affect wildlife (Lyon et al. 2003; Sawyer et al. 2006). Because surface disturbances from hydraulic fracturing development often occur far away from large population centers in Pennsylvania, they often fail to be recognized as a problem. Gas development usually occurs on agricultural land and forested areas. Extracting natural gas requires new well pads, roads, and gas lines, all of which have led to a significant amount of disturbed land (Johnson et al. 2010; Slonecker et al. 2012).

Among ecosystems impacted by hydraulic fracturing in Pennsylvania, forests may feel the most lasting effects of gas development (Drohan et al. 2012). Gas development leads to

actively maintained open swaths of land that bisect continuous tracts of forest. This disturbance has numerous negative effects in that it both acts as a barrier to existing species and introduces new pathways for new species to enter forest systems. In some forests, gas development can represent the first significant surface disturbance in generations. The effect of gas surface disturbance is also pronounced in other, more actively managed forests, where trees are regularly harvested. Of the many types of forest, gas development poses the most lasting and permanent threat to old growth forests in Pennsylvania (Jenkins et al. 2004). Gas development has subdivided large continuous tracts of habitat vital to interior forest species, which thrive in large continuous patches of forest that are far removed from forest edges and human influence. Many species, such as black-throated blue warblers, salamanders, and many woodland flowers thrive in interior forests (Johnson, 2011). These species' habitats are specific to the shade, humidity, and tree canopy protection that only deep forest environments can provide (Johnson, 2011). The impacts of gas development upon forests are often measured through fragmentation statistics, which account for the following five phenomena (Slonecker et al. 2012):

- Reduction in total area of the habitat.
- Decrease of the interior to edge ratio.
- Isolation of one habitat fragment from other areas of habitat.
- Breaking up one patch of habitat into several smaller patches.
- Decrease in the average size of each patch of habitat.

These influences are great and varied, but in the end they indicate a reduction of viable, continuous habitat under which many animals and plants thrive.

The impact of gas development on Pennsylvania's forests is widespread and significant. The Nature Conservancy found that of all natural gas development from the Marcellus shale in Pennsylvania, about 46 percent of pads occurred in forest or forest edge areas (Johnson 2008). A

later study found that roughly 38 percent of pads were in forest cover, and 54 percent of permitted pads were in forested regions (Drohan, 2012). Regardless of the precise number, these studies indicate that roughly half of all gas development occurs in forested areas, and permitting indicates that the number of gas pads in forested regions is likely to increase.

Disturbance from shale gas pads varies depending upon local regulations, the location of the pad, and the number of wells being drilled beneath the pad. The Nature Conservancy determined the average disturbance from all gas development activities, including roads, pads and gas lines, to be 3.6 hectares of direct disturbance and 8.7 hectares of indirect disturbance in the forest surrounding development (Johnson et al. 2010, Table 1.1). Of the 3.6 hectares directly impacted, disturbance stems largely from pipelines used to transport gas to market—in fact their footprint alone is larger than the cumulative impact of roads and well pads.

Table 1.1: Average Spatial Disturbance for Marcellus Shale Well Pads in Forested Context (hectares)		
Forest cleared for Marcellus shale well pad	1.3	3.6
Forest cleared for associated infrastructure (roads, pipelines, water impoundments, etc.).	2.3	
Indirect forest impacts from new edges	8.7	
Total direct and indirect impacts	12.3	

The gathering pipeline rights of way range from are typically around 30 meters, but can range from 10-50 meters wide. These gathering lines stretch an average distance of 2.65 kilometers per well pad. Every mile of pipeline with a 10-meter lateral clearance directly disturbs 4.9 hectares and affects an additional 29 hectares of surrounding forest through edge influences (Johnson et al. 2010).

Forest History

The story of today's forests in Pennsylvania began with the destruction of the prior forests by colonists. Before colonization, over 95% of the state's surface was forested (Johnson et al. 2010). As settlers of European descent began moving to Pennsylvania in the late 1600s, forest resources were rapidly reduced. Forests were consumed by lumber and charcoal production, and agriculture. Pennsylvania forests, at their lowest point, were reduced to a third of their original extent. Since that time, forests have rebounded and now cover 60 percent of the state. Of that forest, only a very small portion of the original old growth, or near old-growth, forest remains. Most of these old-growth forests remain in north-central Pennsylvania and some state parks (Slonecker et al., 2012).

In contrast to the post-colonial recovery that occurred in the 20th century, Pennsylvania forests have seen a net decline in the past decade; part of this loss can be attributed to gas development (Johnson et al. 2010). The Marcellus shale underlies much of Pennsylvania's forests (Figure 1.1), and gas development occurs in over half of Pennsylvania's counties. The densest development reflects the location of the highest yielding areas of the formation—in the southwest, north central, and northeast parts of the state (Johnson 2010). The story of today's forests is much more complicated than that of the forest present during the time of the colonial settlers. Forested land is held by a wide mix of owners and includes private, environmental non-profit, and a wide range of publically owned parcels. The large majority of forest is privately owned. Publically held land exists in subcategories, such as forestry land, state parks, wilderness areas, and sites of natural significance, among others. Each subcategory exists with its own stipulations as to how the land can be used—whether it may be logged, used for recreation, or

held as an environmental reserve. Figure 1.2 demonstrates some of the diverse entities under which forested land may be owned.

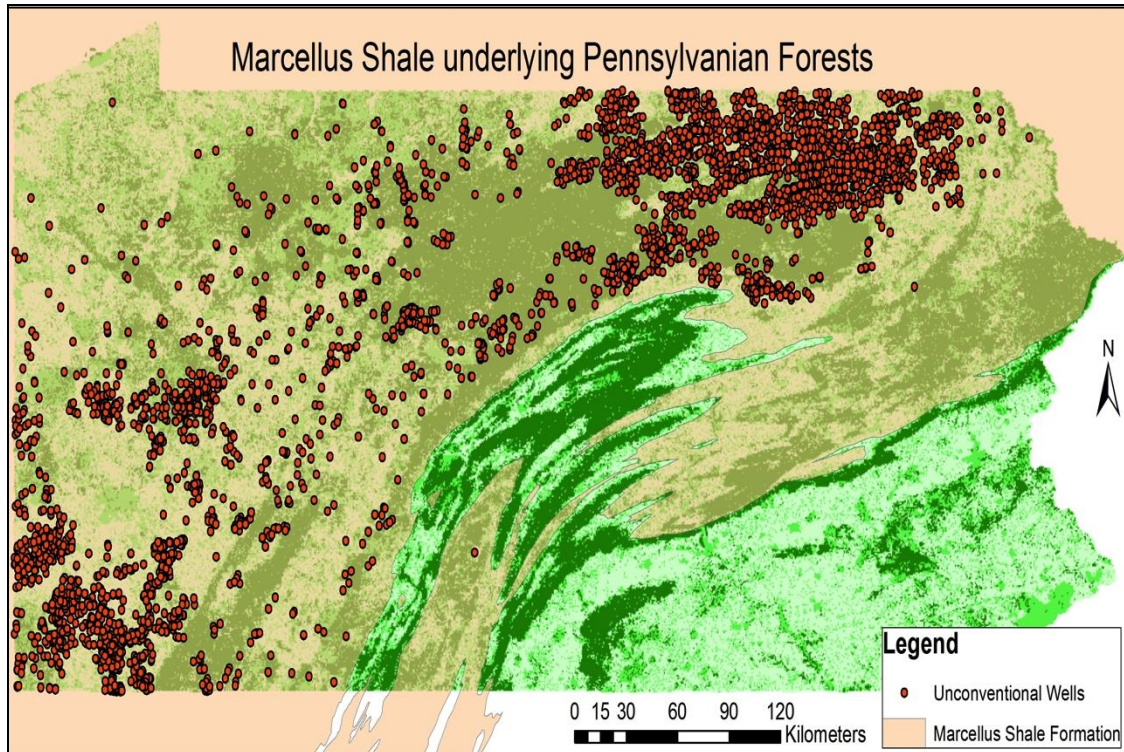


Figure 1.1: Location of Marcellus Shale underlying Pennsylvania's forests and sites of gas development.

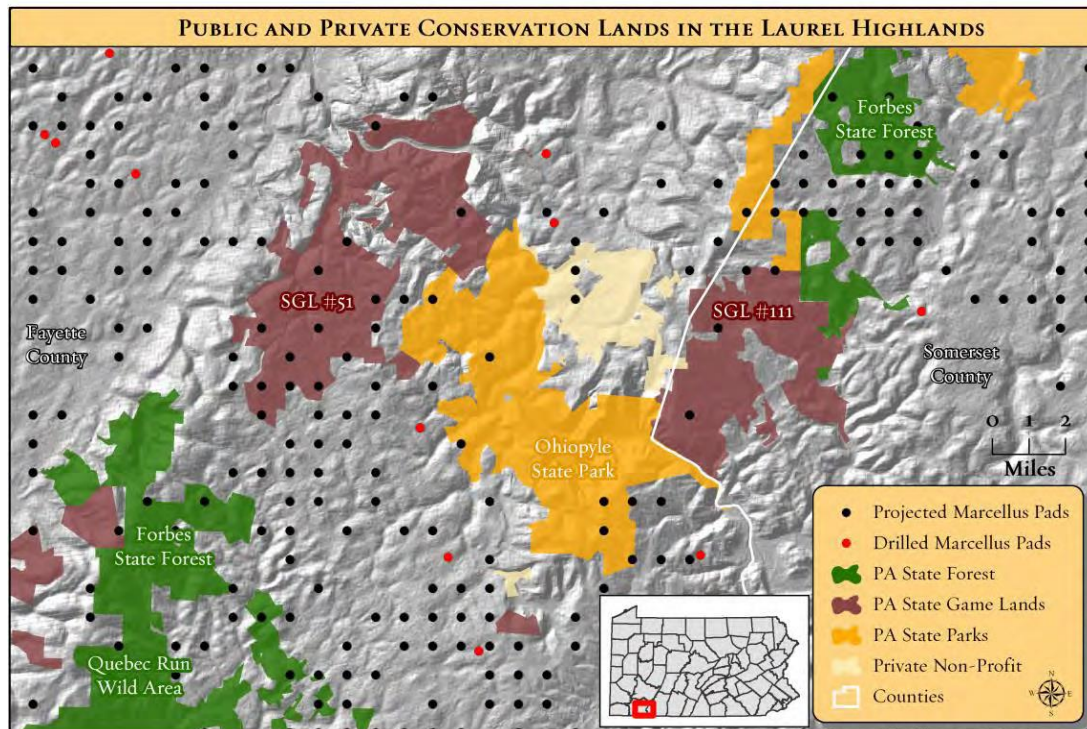


Figure 1.2: Example of the mix of forestland ownership and regulation (Johnson et al. 2010)

Location

The question of protecting Pennsylvania's forests from fragmentation is not as simple as banning gas development from public forestland. The Pennsylvania Department of Conservation and Natural Resources (DCNR) has made it its policy not to extract natural resources from state forestland. However, in many cases, the subsurface and surface rights are severed. Severed rights occur when subsurface mineral rights are owned by an entity separate from the state. The large majority of wells on public land lie under state forests, which exist under different regulations than private land. Severed rights are a result of how these areas were developed. Unlike much of the western United States, the East Coast was subdivided into private land parcels. In many cases, current public forests developed around land unsuitable for development, such as steep sided valleys and ridges. Other publically held forests were built up through gradual land acquisition on the part of the state. In many cases, however, these acquisitions did not also

include mineral rights. The present manifestation of this policy is large forests with mineral rights owned by entities separate from the state. These mineral rights can be sold and leased for gas development without the state's approval (Dycus, 1980).

A further source of gas development in Pennsylvania public forests is the large mineral leases that the state made from 2008-2010 to balance the state budget (PA DCNR, 2012). The Marcellus Shale underlies approximately 600,000 hectares of the 900,000-hectare state forest system. Of those 600,000 hectares, 280,000 hectares are available for development. There are 117,000 hectares of leases on land with severed rights. A large portion of the remainder, 156,000 hectares, was leased from 2008-2010, leasing this land generated over \$413 million in revenue for the state (PA DCNR, 2012a). Figure 1.3 displays forestland that has been leased or exists on land with severed rights. Currently there is a ban on further leasing deals, but as lawmakers seek to balance the fiscal budget, this source of revenue remains tempting, making study of environmental impacts of gas development extremely urgent.

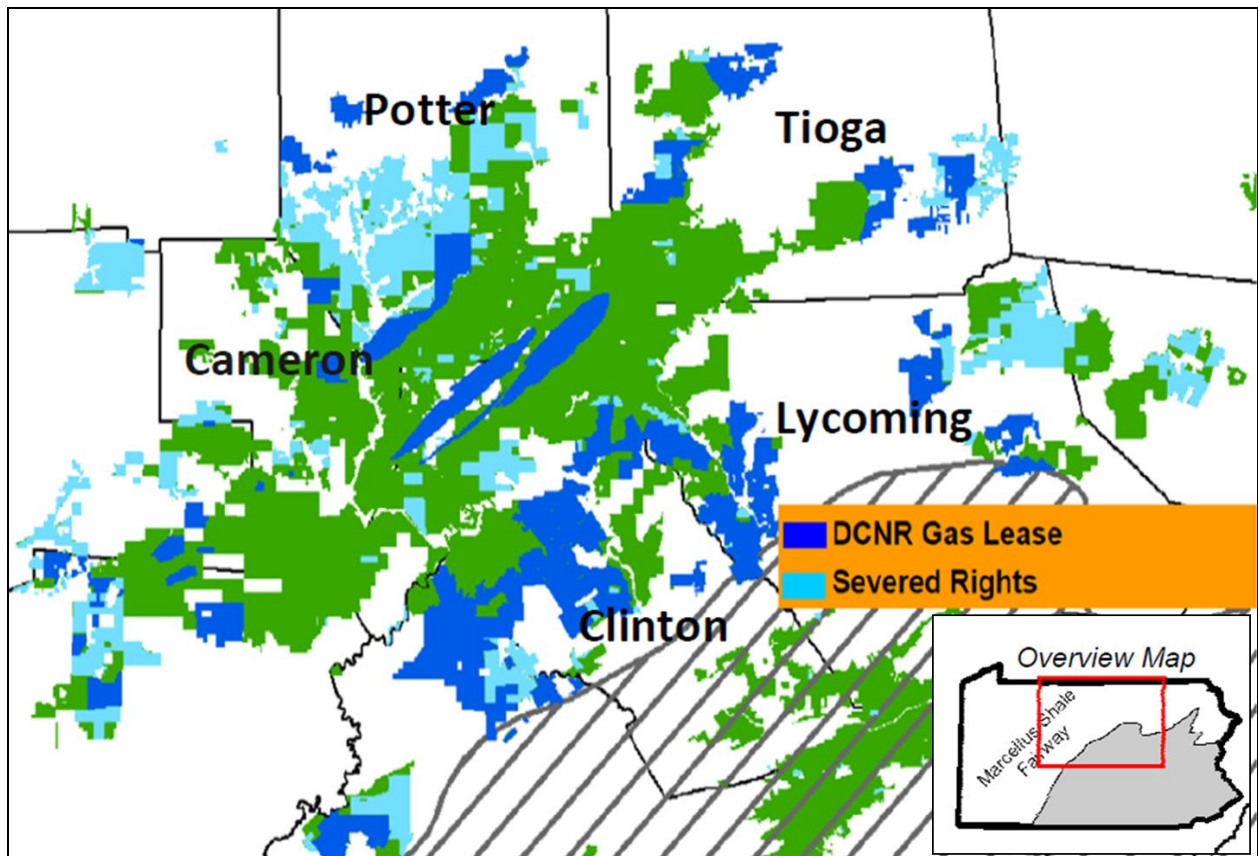


Figure 1.3: Location of PA DCNR gas leases (dark blue), and severed rights (light blue) on public forests (green). This site is Pennsylvania’s most heavily forested region (PA DCNR, 2012b).

Prior Studies

There have been several studies evaluating the effects of gas development upon forestland in different regions (Adams et al. 2011; Johnson et al. 2010, Sawyer et al. 2006; Slonecker et al. 2012). However, these analyses vary in the specifics of their studies, some were performed in Alberta, and others in Pennsylvania, similarly, they varied in what they studied. The Nature Conservancy prepared a report in which they made several development projections for the year 2030 (Table 1.2; Johnson et al. 2010). Their data indicate a loss of less than 1 percent of that state’s total forest acreage at its highest development. However, this 1 percent loss would lead to a 2-3 percent loss of local forest habitats.

Table 1.2: Johnson's (2010) Projections of Marcellus Shale Gas Development through 2030 (hectares).			
Development Scenario	Low	Medium	High
Number of pads in forested areas	4,310	6,950	10,250
Total cleared forest (3.6 hectares/pad)	15,000	25,000	36,000
Indirect effects to adjacent interior habitats (8.7 hectares/pad)	37,000	59,000	89,000

The Nature Conservancy created this projection in a multilevel comprehensive study of energy impacts in Pennsylvania. Their analysis entailed the use of 50 spatial data layers, spatial footprint analysis, scale and geographic projections, and conservation impacts analysis. This analysis not only assessed the present footprint of gas development and impact upon forest patches, it also considered the effect upon at-risk patches of high-biodiversity. My study also assessed methods of reducing gas development's impacts.

More recently, the United States Geological Survey (USGS) has published the article *Landscape Consequences of Natural Gas Extraction in Bradford and Washington Counties, Pennsylvania, 2004-2010*. This article, while not as broad in geographic extent as the Nature Conservancy's study, provides fragmentation statistics, such as parcel size, edge, interior forest, dominance, and contagion, metrics that are outlined in Table 1.3. Landscape metrics enable a more in-depth interpretation of landscape effects of gas development than The Nature Conservancy's Study (Slonecker et al. 2012). However, Bradford and Washington counties are not in areas of major forestation. Rather, they are 50-60 percent forested as compared to my study's site, which is more than 90 percent forested (Johnson et al. 2010).

Table 1.3: Landscape Metrics (Slonecker et al. 2012).		
Term	Definition	Concern
Interior Forest	Forest at least 100 meters from the forest edge, a measurement of area	Environmental conditions differ from areas closer to the forest edge. Interior forest is related to the size and distribution of forest patches and is critical to many species (Harper et al. 2005).
Forest Edge	Linear measure of the length of edges between forest and other land uses in a given area.	When edges expand into ecosystems, the ecosystem can be affected some distance in from the edge (Skole and Tucker, 1993).
Contagion	The degree to which adjacent land uses can be found in the landscape.	This is an important measure of how landscapes are fragmented by patches. A higher value indicates a less fragmented landscape (McGarigal et al. 2002).
Fractal Dimension	The complexity of patches or edges within a landscape. Generally measure of perimeter to area proportion.	Human landscapes, e.g. fields, tend to have low-complexity shapes. In contrast, natural cover has complex edges and a higher value of fractal dimension.

This thesis incorporates the data and methods of both of the Nature Conservancy and USGS studies to analyze the fragmentation effects of gas development upon Pennsylvania State Forests that are part of Pennsylvania’s proposed old growth forest system. Similar to Slonecker and others’ research (2012), this study utilizes landscape analysis (Table 1.3). Landscape analysis creates metrics which may be used to understand and characterize disruption. These metrics enable scientists to understand the relation between landscape patterns and ecological relationships, such as habitat, conservation, and sustainability. In summary, this thesis explores the current level to which gas development has affected forests that are a part of Pennsylvania’s proposed old growth forest system through the use of landscape metrics.

Chapter 2: The current state of Pennsylvania's Forests

Pennsylvania's forests provide habitats for thousands of plant and animal species, clean water and air, recreation, and wood products (PA DCNR, 2010). These forests have been increasing in size and quality from their low point in coverage 100 years ago (PA DNCER, 2010). The recovery process has not been quick, and it is not an indicator of the forests' future wellbeing. There have been sweeping changes in the forests throughout the past century as forests have faced a number of issues from invasive species and droughts to urban sprawl. Marcellus shale gas development is only the most recent wave of change inflicted on Pennsylvania's forests. This chapter outlines changes in Pennsylvania's forests, gas development's role in those changes, gas regulation in forested regions, and forest restoration plans.

Forest History

Before European colonization more than 90% (11 million hectares) of Pennsylvania's surface was forested (PA DCNR, 2010). There have been many changes in Pennsylvania's forest cover from 1630 to 2004 (Figure 2.1). Beginning in the 1860s, Pennsylvania forests saw a steep decline in coverage as land was cleared for development, agriculture, and lumber (DeCoster, 1995). By the 1900s, industrial timbering and agriculture reduced this cover to only 32% of the state's land area (3.7 million ha). Any intact forest after this period was transformed into structurally homogenous early-successional forest as diverse multi-age forests were lumbered and simply replanted in one swath. Wildfires further simplified the remaining forests by eliminating coarse

woody debris and scorching soils (Jenkins et al, 2004). These simple forests 90-120 years ago formed the basis for today's forests (PA DCNR, 2010). Pennsylvania's forest cover gradually increased from the early 1900s and stabilized in the 1960s. Since that time forest cover has remained relatively constant at 6.5 million hectares of timberland, though recent decades have seen a slight decline in coverage (PA DCNR, 2010).

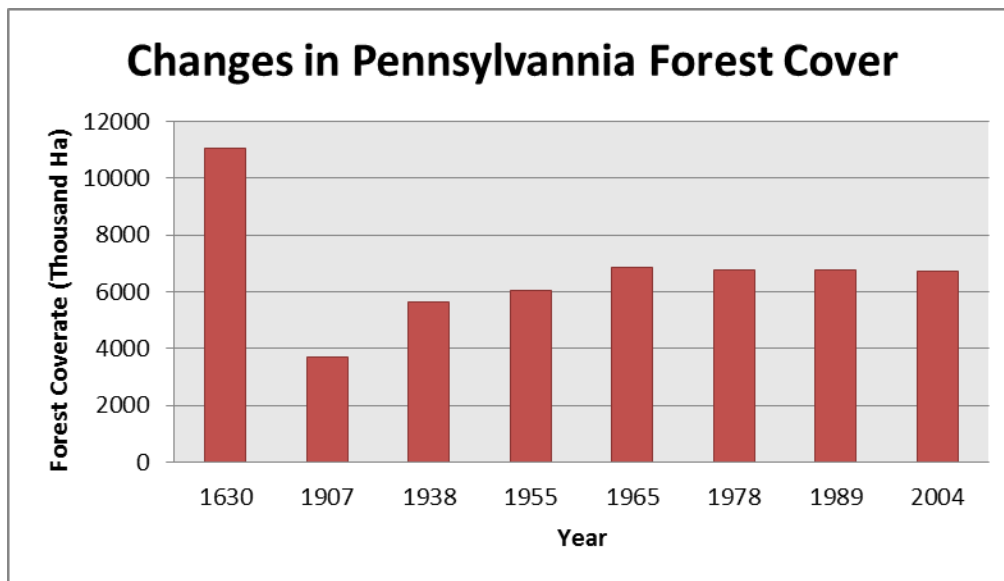


Figure 2.1: The area of PA forest cover from 1630 to 2004 (PA DCNR, 2010).

Urban sprawl has been the largest threat to forests in recent decades (PA DCNR, 2010). However, due to public acquisitions of threatened forestlands into the state forestry and parks system, Pennsylvania's forest cover has remained constant (PA DCNR, 2010). The largest gains from Pennsylvania's forest acquisition program occurred in the early 2000's (Figure 2.2). The rate of acquisition is steadily declining, however, as funding for these programs disappears (PA DCNR, 2010).

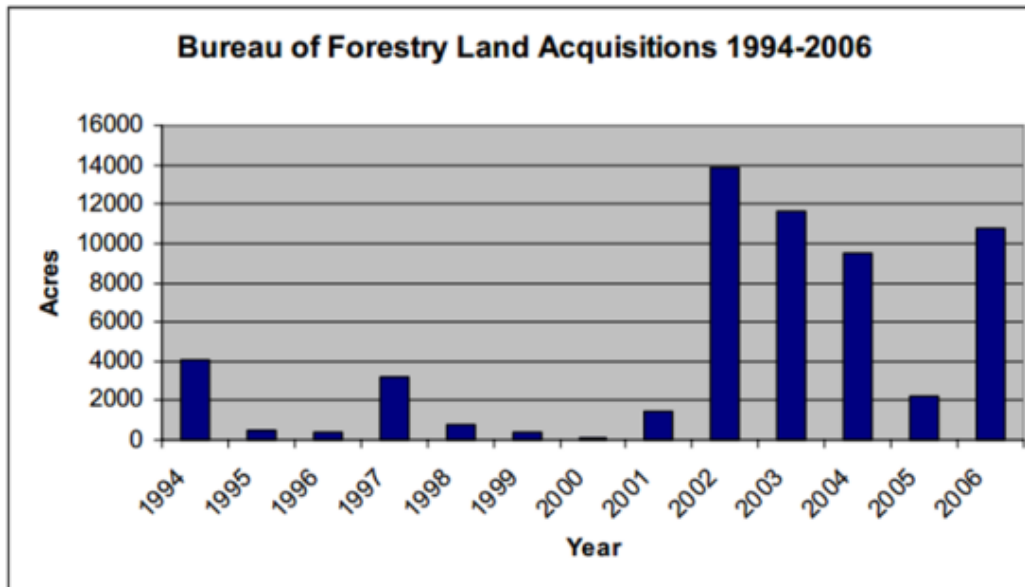


Figure 2.2: Size of Bureau of Forestry Land Acquisitions from 1994-2006 (PA DCNR, 2010).

Today over 600,000 entities own Pennsylvania's 6.5 million hectares of forestland (Figure 2.3). The majority, 4.55 million hectares (70%) of forestland, is privately owned. This portion of land is particularly susceptible to increased fragmentation through parcelization and development. As the average landowner is 50-60 years old, a large proportion of this forestland is likely to exchange ownership within the next 20 years. The remaining 1.95 million hectares of forestland (30%) is publically owned (PA DCNR, 2010). Of that land, 247,000 hectares (4% of total forest cover) are federal land and are protected, while the state owns 1.54 million hectares (23% of total forest cover). The remainder of public land is owned and managed by local governments. Figure 2.4 outlines all publically managed as well as privately held and protected forestland in Pennsylvania.

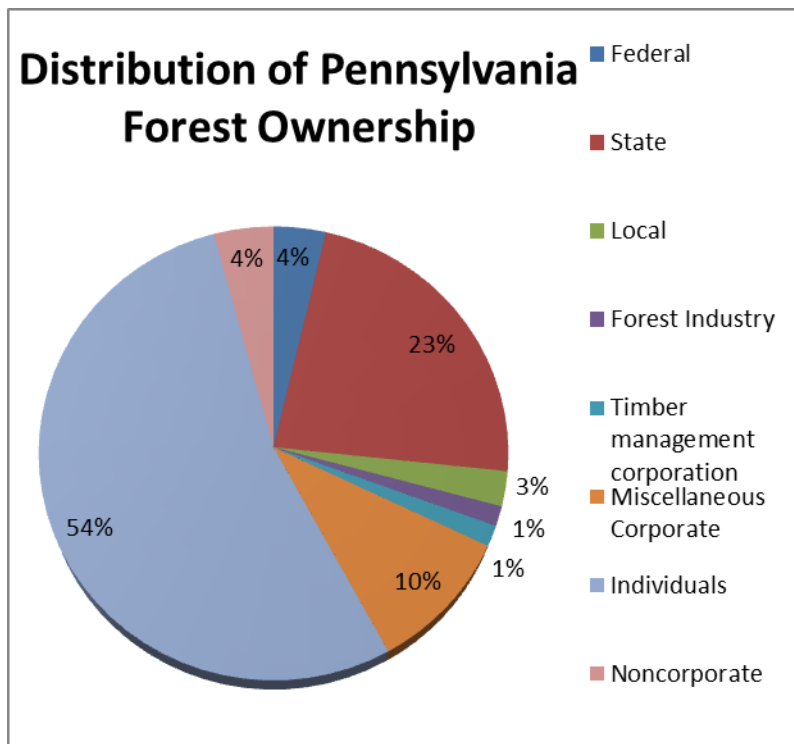


Figure 2.3: Distribution of forest ownership in Pennsylvania (PA DCNR, 2010).

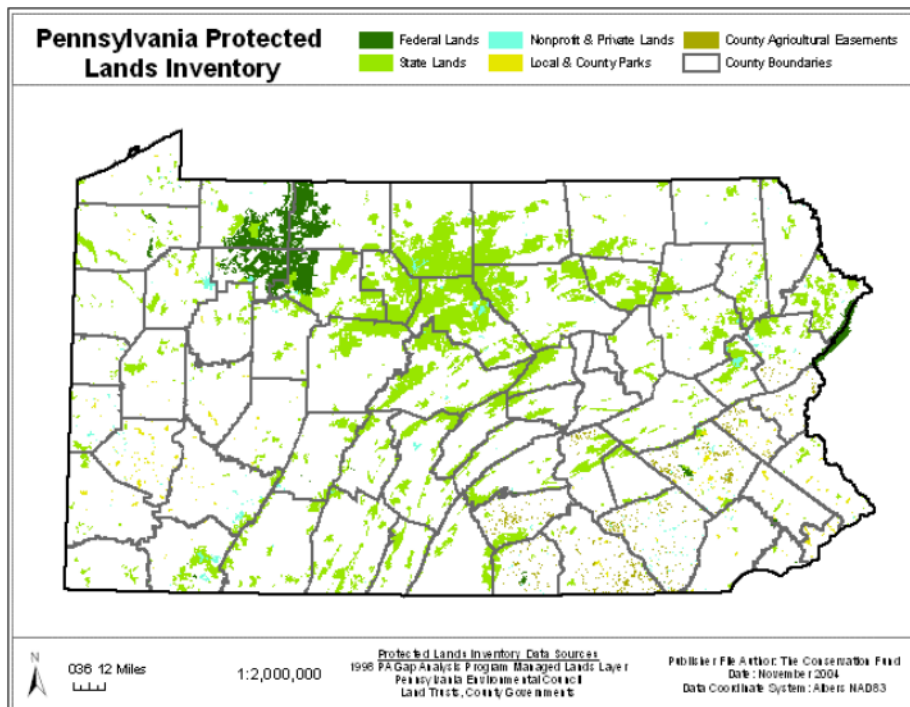


Figure 2.4: Publicly owned and managed lands in Pennsylvania (PA DCNR, 2010).

Oil and Gas in Pennsylvanian Forests

Pennsylvania has been home to oil and gas development for over a hundred and fifty years. It was home to the first-ever commercial oil well in 1839. Since that time, more than 350,000 oil and gas wells have been drilled in Pennsylvania (PA DCNR, 2010). In 1947, the Pennsylvania Department of Conservation and Natural Resources (DCNR) first leased state forestland for natural gas extraction (PA DCNR, 2010).

The most recent and largest group of leases in state forests by the DCNR has occurred due to the Marcellus shale. The Marcellus underlies approximately 600,000 hectares of the 890,000 hectare state forest system. Of those, 270,000 hectares are available for gas development, meaning they are leased or have the potential of being leased, as is exhibited in Figure 2.5 (PA DCNR, 2012). Shale gas is allowed on areas previously permitted for shallow gas drilling. The mineral subsurface rights to 120,000 hectares of PA forestland are privately held and have been severed from surface ownership of that land. This land is subject to gas development, from which the State does not receive any rents or royalties (PA DCNR, 2012). The remainder of forestland leases has been issued by the state; they total approximately 156,000 hectares (PA DCNR, 2012). Much of this land was leased in a set of three leases totaling 56,197 hectares for \$413 million (Table 2.1; PA DCNR, 2012). As of 2012, leases have generated \$100 million in royalty revenue for the state from 276 drilled and producing gas wells (PA DCNR, 2012). Funds from leases and production originally contributed to Pennsylvania's Oil and Gas Lease Fund (DA PCNR, 2012), which has been used to support conservation, recreation, flood control projects, and the continued expansion of Pennsylvanian forests. However, more recently funds have been used to balance the state government budget (PA DCNR, 2012).

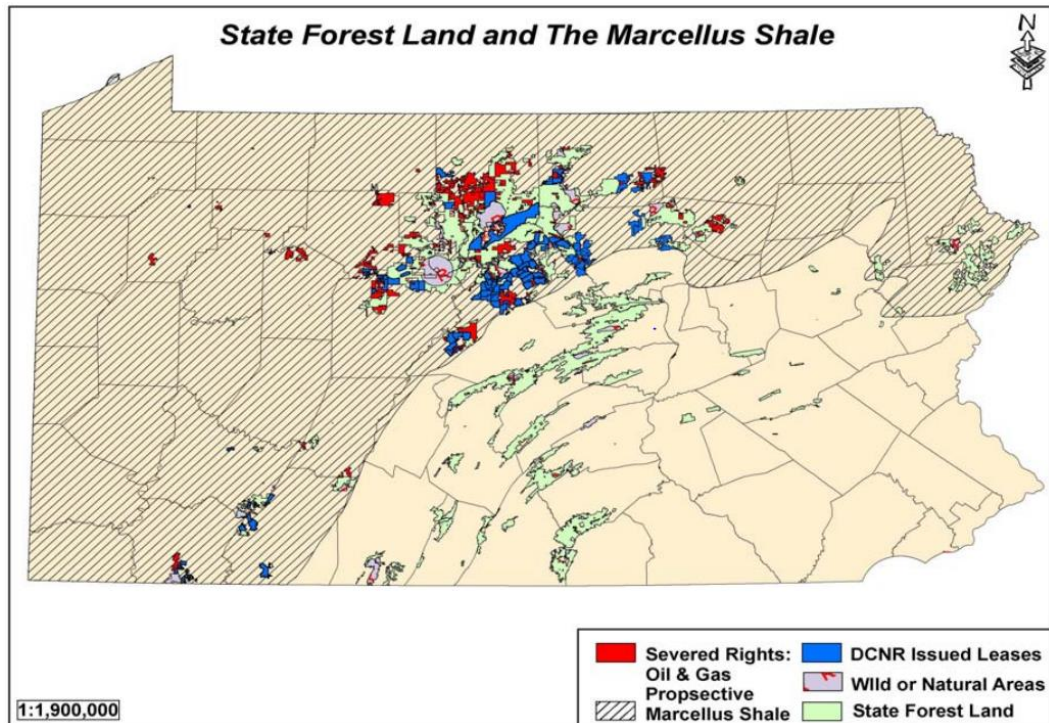


Figure 2.5: The Marcellus shale, Pennsylvania forests, and leases (PA DNR 2010).

	Year	Size (hectares)	Lease Sale Price (million)
Lease 1	2008	29,956	\$163
Lease 2	2010	12,928	\$130
Lease 3	2010	13,313	\$120
Total		56,197	\$413

Between conventional and shale-gas wells there were over 750 producing gas wells on 267,000 hectares of DCNR land at the close of 2009 (PA DCNR, 2010). Drilling is not permitted on a large amount of the remaining DCNR acreage in the Marcellus gas play as these lands are designated as Wild, Natural, sensitive ecological, and recreation areas (PA DCNR, 2012). The DCNR has approved 211 well pads and 842 shale gas wells on public forest land since 2008 (2008-21; 2009-179; 2010-284; 2011-315; 2012-55). Each well pad can host 6 to 24 wells (PA DCNR, 2013). However, typically well pads at this early point of gas development usually consist of fewer than 6 wells.

Drilling regulations

The PA DCNR has stated that Marcellus Shale gas development “will challenge existing policies and guidelines” (PA DCNR, 2010). Current regulations provide most strongly for water and soil protection (PA DCNR, 2010). However, several best management practices and regulations attempt to minimize habitat fragmentation from gas development. These practices and regulations address issues related to well-pad size and road and pipeline rights-of-way. For example, well pads must be located beyond a certain buffer from Wild and Natural areas. Buffers usually range from 60-180 meters in size (Table 2.2). After well pads are created the cleared area surrounding the pad is restored. The well pad itself is to be fully restored when the well finishes production and the company owning the pad determines they will no longer be drilling or accessing the well pad. Reclamation is dependent upon management goals, local species, and habitat needs. Restoration includes the following steps: return site to original contours, spread topsoil over site, re-vegetate using a “*predominately native seed mix*,” etc. (PA DCNR, 2013). Pads may be restored to their original forested status, or another purpose the serves the local ecosystem, depending upon management goals. Possible pad restoration options include the following: regenerating forest, small forest opening, herbaceous opening, successional opening, and wetlands.

Table 2.2: Buffer sizes around well pads in relationship to key ecological features (PA DCNR, 2013)	
Area	Buffer (meters)
Wild and Natural Areas	180
Exceptional value or high quality stream or body of water	90
Picnic areas or trails	90
Wetlands	60
Wetlands with threatened and endangered species	90

In addition to well pads, other components of disturbance include pipelines and roads. Current DCNR policy places shale-gas pads and pipelines as close as possible and parallel to existing roads. In general, the DCNR tries to cluster pads to minimize overall forest disturbance from pipelines, roads, and pad disturbances (Drohan et al, 2012). Pipeline development is not allowed in parks, wild or natural areas, but it is acceptable in state forests (PA DCNR, 2010)

Present Ecological State

A sustainable forest is able to produce the full suite of ecological, economic, and social benefits and services for both current and future generations (PA DCNR, 2010). The current ecological state of Pennsylvania's forests has been determined by a number of indicators through the Montreal Process. This process is a sustainable forest management protocol that was developed in Geneva, Switzerland as a result of *Forest Principles* developed at the 1993 Earth Summit.

In general, forests do not exist at a permanent non-damaged and high-functioning ecological state. In fact, "nearly every acre of forest in Pennsylvania has been affected by a damaging agent" (PA DCNR, 2010). Forests are susceptible to environmental stressors and damaging agents such as insects, diseases, invasive plants, white-tailed deer browsing, wind gusts, drought, climate change, air pollution, poor management decisions, and wildfire (PA DCNR, 2010). As such, even forests that appear green and thriving from above may be full of dying trees and have rapidly declining diversity. There are 18 key characteristics that have been used to indicate the state of Pennsylvania's forests (Figure 2.6). Characteristics are have been valued as being unsustainable (poor quality) to sustainable (largely capable of maintaining itself). Damaging agents, forest conversion, and current forest characteristics demonstrate the most unsustainable trends in these forests.

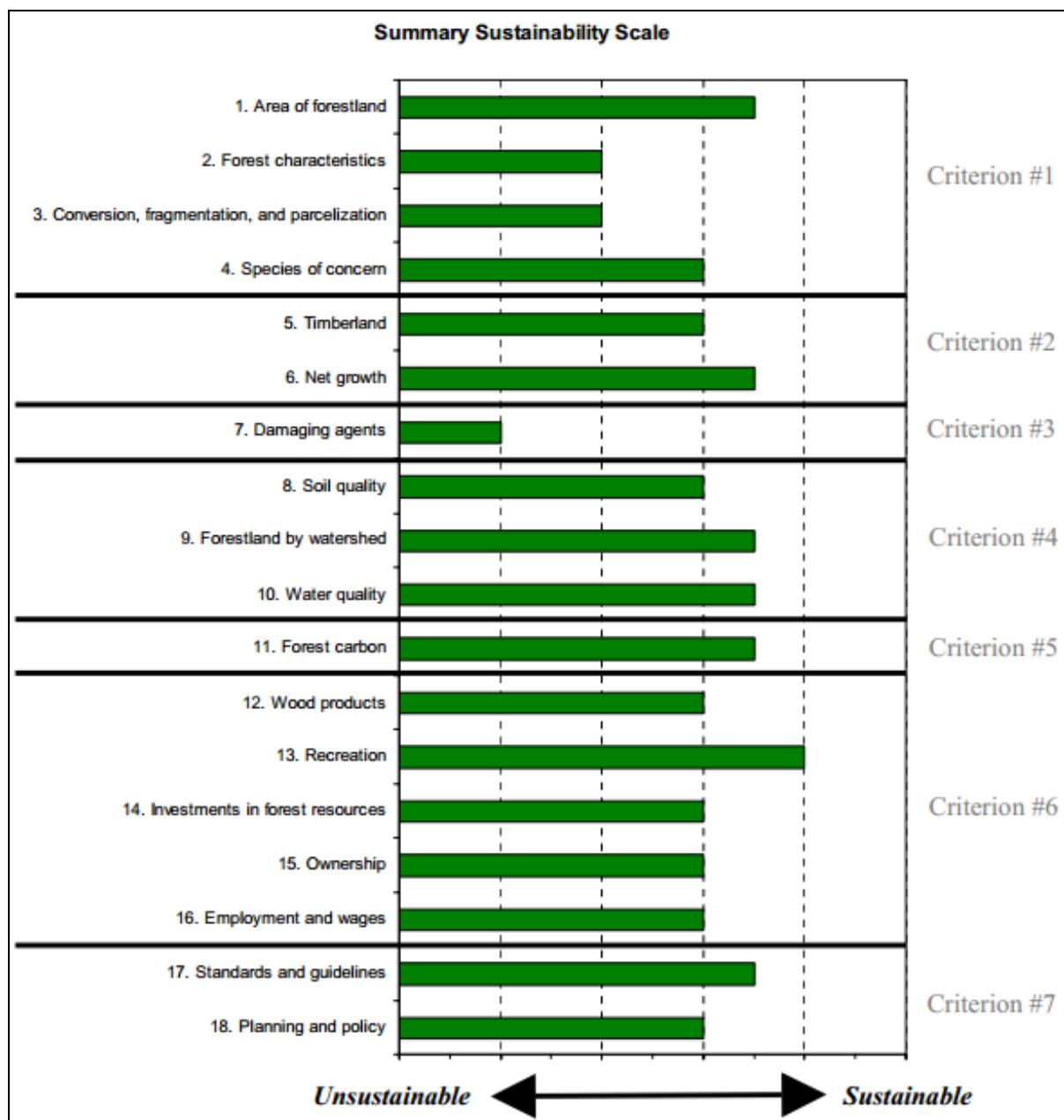


Figure 2.6: Sustainability rating of 18 key features of Pennsylvania's Forests (PA DCNR, 2010).

Pennsylvania's forests host remarkable biodiversity. There are over 25,000 species in the state, and many of them rely upon forests. Pennsylvania's forests contain over 100 tree species. There are two primary types of forest coverage—oak/hickory dominated and maple/birch dominated. Oak/hickory forest contains mainly oaks, maples, and hickories. Maple/birch forests

consist of black cherry, maples, American beech and birch. The current forest make-up is changing, however. Sugar maples, hemlock, beech, and oaks are declining. This shift indicates a drastically different future forest composition, with unknown consequences for the wildlife that relies upon these species (PA DCNR, 2010). Forests will continue changing under projected climate change scenarios. Many species' habitats will shift to the north and to higher elevations (PA DNCR 2010). Another factor influencing forest type changes has been invasive species, which are outlined in Table 2.3. Controlling pests is both energy and resource intensive and may not be effective (PA DCNR, 2010).

Table 2.3: Major Host Species and Damage-Causing Agents in Pennsylvania (PA DCNR, 2010)	
Host Species	Major Damage-Causing Agents and Potential New Invasive Species
Oaks (all species)	Gypsy moth; drought; oak wilt; bacterial leaf scorch; red oak decline; white oak decline; <i>P. ramorum</i> (SOD); oak leaf-tier; climate change
Maples (all species)	Forest tent caterpillar/anthracnose; Asian longhorned beetle; Sugar maple decline; fall cankerworm; elm spanworm; drought; acid precipitation; climate change
Eastern hemlock	Hemlock woolly adelgid; elongate hemlock scale; drought; Fabrella needle cast; climate change
Ash (all species)	Emerald ash borer; ash yellows; ash decline drought; fall cankerworm; climate change
American beech	Beech bark disease (scale insect, exotic and native <i>Nectria</i> cankers); drought; elm spanworm; climate change
Walnut, butternut, and elm	Thousand cankers disease & walnut twig beetle; butternut canker; elm yellows
Pines (white, red, and other <i>Pinus</i> spp.)	<i>Sirex noctilio</i> ; Common pine shoot beetle; <i>Orthotomicus erosus</i> (Mediterranean pine engraver); <i>Ips pini</i> ; other exotic bark beetles; drought; climate change

Current effects of gas development on forest fragmentation

The Pennsylvania Department of Conservation and Natural Resources has stated that gas exploration and extraction in Pennsylvania has the potential to permanently change existing natural habitats into well pad sites (PA DCNR, 2010). The PA DCNR believes that the

expansion of drilling is likely to accelerate the current rate of forest fragmentation in Pennsylvania for the next 10-20 years (2010). In 2010, 38% of well pads occurred in forested areas (Figure 2.7; Drohan et al. 2010). The amount of disturbed land from Marcellus Gas development is projected to increase 81% over the state of development in 2010 (Drohan et al. 2010).

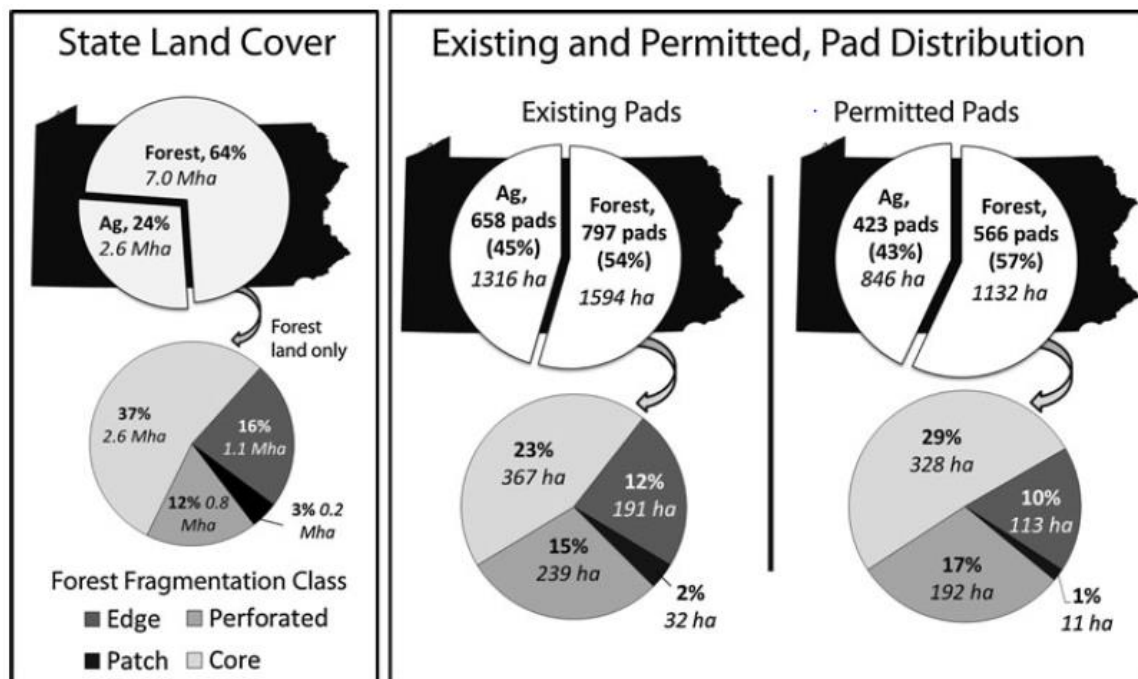


Figure 2.7: Statewide distribution of forest and agricultural lands and forest fragmentation classes (Mha refers to million hectares). There are four forest fragmentation classes: edge, patch, perforated, and core. This indicate the presence of wells in forests, whether they are located on the edge of forests, their core, perforated forest which already contain many clearings, or small, isolated forest patches. Note that the remaining 1% of existing pads occur on already disturbed land (Drohan et al, 2012).

Shale-gas development in Pennsylvania occurs in a wide range of conditions, private and public land, forests, and fields. The greatest portion of development is on private land.

Approximately 45–62% of pads occur on agricultural land, and 38–54% in forestland. Drohan et al.'s (2012) research indicates that gas development on PA public forestland has been more

effectively managed than private forests experiencing gas development. PA public forestland has a higher ratio of pads to miles than PA private land, meaning it has more pads developed for every adjoining amount of developed road, meaning that gas is more effectively developed in terms of surface disturbance on public rather than private land (2012). Development of permits granted as of June 3, 2011 would convert 536–894 ha of forestland into well pads (Drohan et al. 2012). If all existing permits were developed there would be over 650 km of new roads created. In addition to pipeline construction, developing these pads and roads would significantly fragment forest cover (Drohan et al. 2012). Not only do well pads fragment core forest, but their roads present key vectors of invasive species movement (Table 2.3), which can be “profoundly expensive” and difficult to properly address (Drohan et al. 2012). Evidence of fragmentation effects from gas development have begun exhibiting themselves in the 700 ha Marcellus Gas development in core forest (Drohan et al. 2012). Current well pads are not being utilized as fully as possible. An overwhelming majority of pads host only 1 to 2 wells; fewer than 10% of pads have five or more wells (Figure 2.8). The number of wells per pad will increase as the boom in constructing well pads slows and more wells begin being drilled on each pad. Therefore, it can be expected that the rate of fragmentation will eventually slow even as gas production further increases.

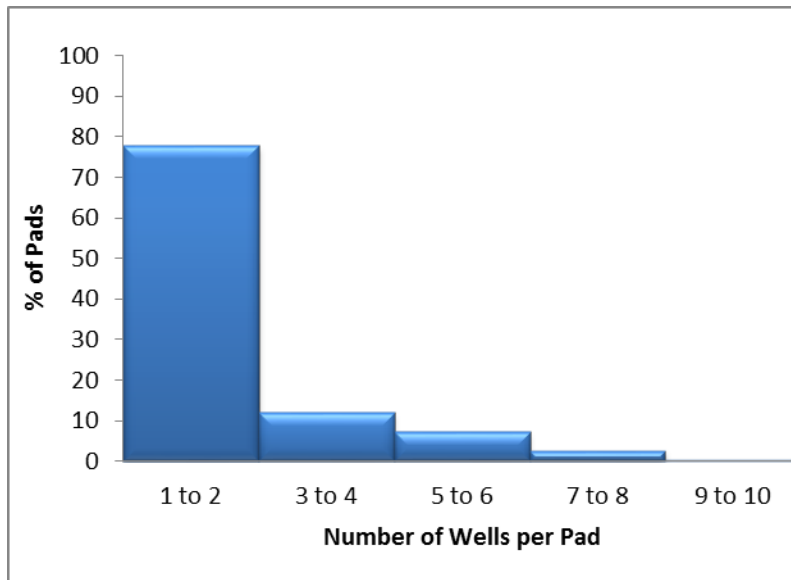


Figure 2.8: Number of wells as a percentage of all pads (Drohan et al. 2012).

Future Plans

Pennsylvania's forests still have a long way to go to reach their ecological state prior to European colonization. They no longer have the extent or biological diversity they used to possess, and they are still at risk from invasive species and increased fragmentation from natural gas development. Regenerating Pennsylvania's forests will require coordinating management and mitigating impacts and stresses across multiple levels of government agencies and natural resource program areas (PA DCNR, 2010). Current forest regeneration plans include timber harvesting. Harvesting timber, however, aids white-tailed deer, whose intensive browsing encourages the spread of invasive plants as well as pests and pathogens (PA DCNR, 2010). High-grade logging has also changed forest composition. By affecting plant diversity and tree regeneration logging has reduced oak coverage and increased red maples. These, and other problems, must be addressed if Pennsylvanian forests are to continue enriching the states biodiversity.

Despite these problems, there is hope for the future of Pennsylvania's forests. Jenkins and others (2004) proposed a plan to restore a large portion of Pennsylvania's old growth forest system by designating a large portion of public forest as old-growth, which would protect it from development and would allow it to grow in biodiversity over time. The program would utilize the land acquisition program to acquire key forest parcels; it would also designate of key state forest patches to higher protection levels, and utilize forest management practices and guideline that highlight connectivity (Grace, 2003). Currently only 8,000 hectares of old growth remain in Pennsylvania's state forest system. Another 8,000 hectares exist on State Park, Forest Service, and privately owned lands (Jenkins et al, 2004). The proposed old growth system, once completed with additional lands incorporated, would be the second largest restoration of old growth forest in the eastern U.S. after the Adirondacks in northern New York (Jenkins et al, 2004). At 213,000 hectares, it would make up one quarter of the 850,000 hectare state forest system (Figure 2.9).

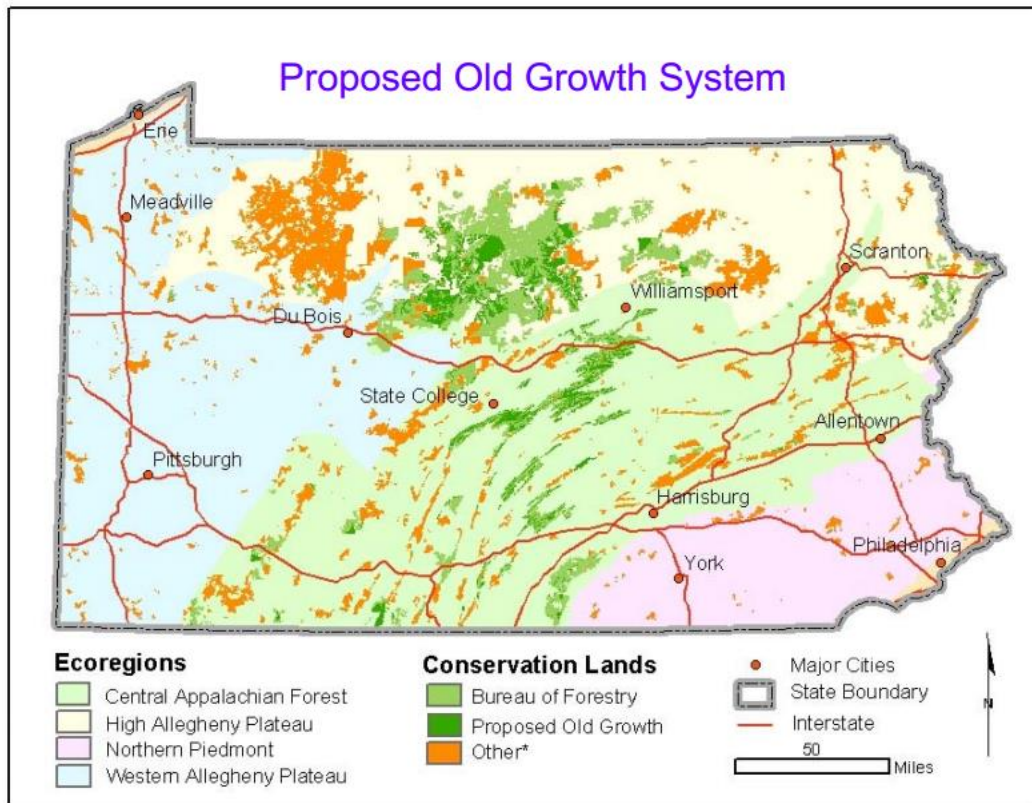


Figure 2.9:

The proposed old growth forest system is outlined in dark green (Jenkins et al, 2004).

The old-growth system would enclose and be composed of natural areas (34,000 hectares), wild areas (60,000 hectares), and limited-resource zones (130,000 hectares). Some of these zones already enclose existing old-growth forests (Jenkins et al, 2004). The present age distribution of forests in the old-growth system would shift from the young trees it currently consists of, to a forest of distributed trees ages and old trees (Figure 2.10). There are currently 70,000 state forest stands, that is, individual forest patches. Under the old growth plan they will be combined to form 1,149 old-growth patches that will average 306 hectares in size. In this system, adjacent forests would act as buffers, and the state forestry office will increase the rotation ages and use active forest management to increase forest diversity at the stand level. This plan differs from forest management that focuses at the forest level and does not employ active management. It would employed active thinning of the forest to ensure distributed forest

age structure as opposed to the current distribution which is bell-shaped (Figure 2.10; Jenkins et al, 2004). Poiani and others (2000) discovered that roughly 15,000 acres of continuous mature forest is necessary to maintain a representative biodiversity of a region. Current old growth forests do not yet approach that critical size, but they are capable of reaching it if this plan can be fully implemented. Pennsylvania's forest has experienced continuous waves of abuses for over 150 years. If the proper actions can be taken to minimize or eliminate this tide, it will be possible to restore the splendor this forest once had.

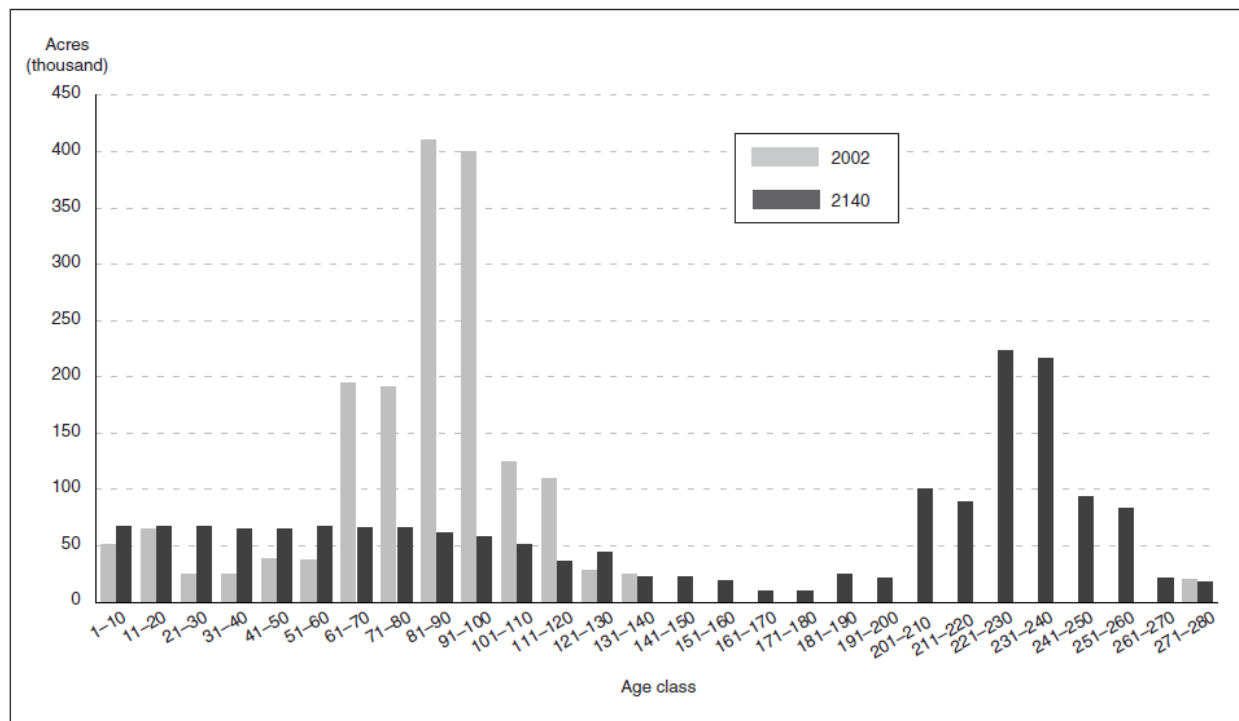


Figure 2.10: The current age class distributions of Pennsylvania's public forests are outlined in gray, with projected age class distributions in the old growth restoration plan shown in black (Jenkins et al, 2004).

The core portion of this proposed old growth plan lies at the center of my study. The old-growth restoration plan was created before the Marcellus shale was a viable energy resource. Now, with the spread of gas development on privately held mineral rights on forestland and on lands leased by the state government, the old-growth plan could be significantly affected. My

study aims to explore the degree to which forest development may affect fragmentation in the old growth system.

Chapter 3: Defining Old-Growth

The term “old-growth” conjures up images of soaring forest trees. Old growth forests are often referred to as natural, primary, primeval, pristine, relict, and virgin—a collection of terms with widely different interpretations (Wirth et al. 2009). White and White (1996) describe old growth forests on the basis of several characteristics: “distinctive and diverse structure that includes trees of various ages, standing dead trees of various diameters, significant coarse wood debris in different states of decay, pit and mound microtopography, and diversity of herbaceous species, soils undisturbed by humans, and soil organic matter, and forest interior invertebrate and vertebrate species.” This definition, however, only describes a very specific type of old-growth forest. In some cases only a few of these characteristics may be seen in old-growth forests. A survey of 39 publications (Wirth et al. 2009) reveals the variable definitions of old growth (Figure 3.1). Old growth forests used to cover huge swaths of the United States. Now they consist of less than 0.5% of its forest area (Wirth et al. 2009). If the features that characterize old-growth forests are understood and promoted, then appropriate regeneration plans to reach highly diverse mature forests can be made.

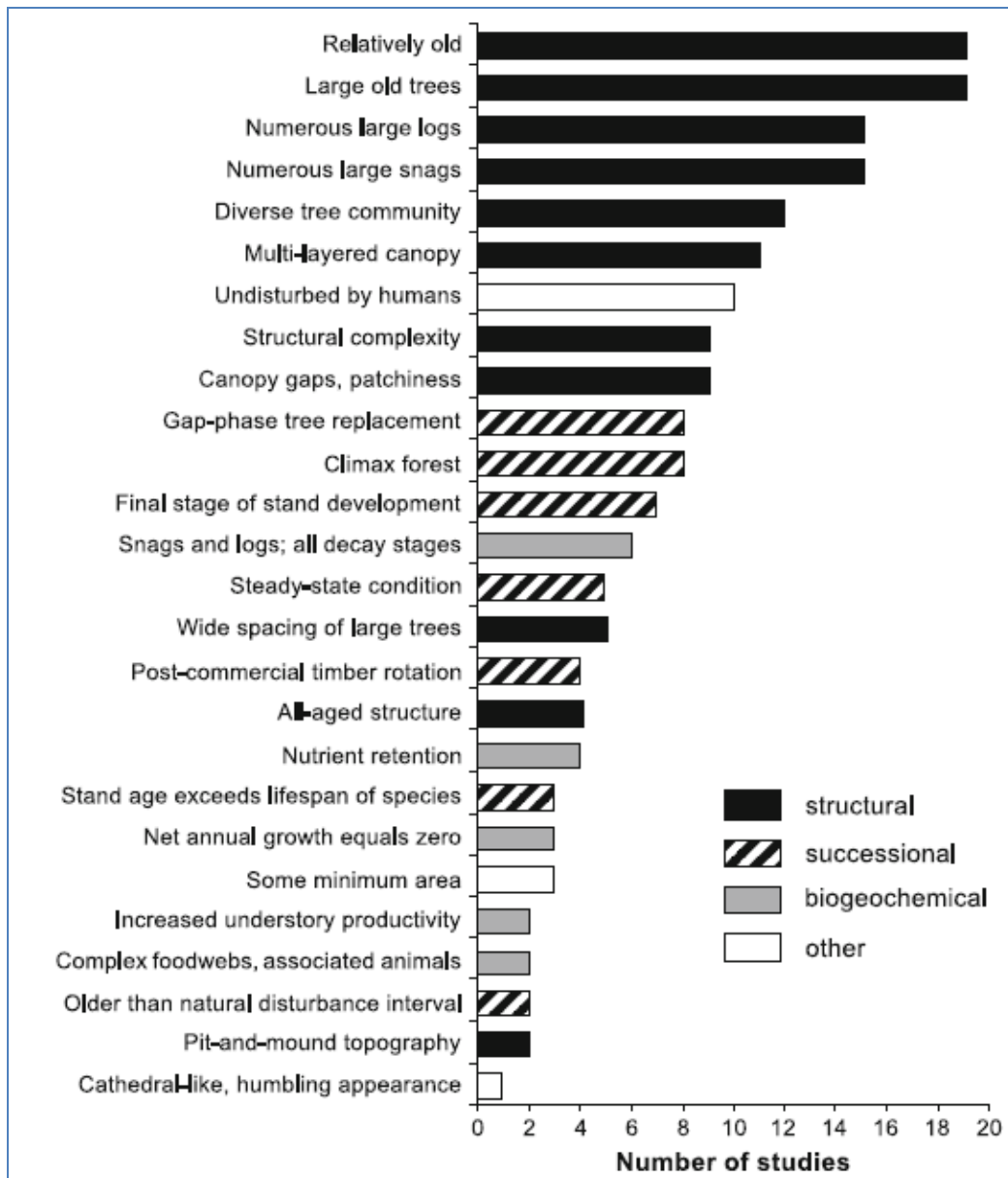


Figure 3.1: Frequency with which different criteria have been used to describe old-growth forest in 39 publications (Wirth et al., 2009).

The study of old-growth forests is not a new one (Wirth et al, 2009). Yet, as Figure 3.2 exhibits, the terminology and criteria defining old growth have varied considerably over the years. Old growth has been referred to anything from “relatively old” to “all-aged structure.” Figure 3.2 defines old growth as largely time and human dependent, true old growth takes a long time to develop under minimal human influences. Often the age and degree of human impact are

not easy to determine, scientists use the groups of indicator systems to determine if forests are old-growth: structural, successional, and biogeochemical indicators (Wirth et al, 2009).

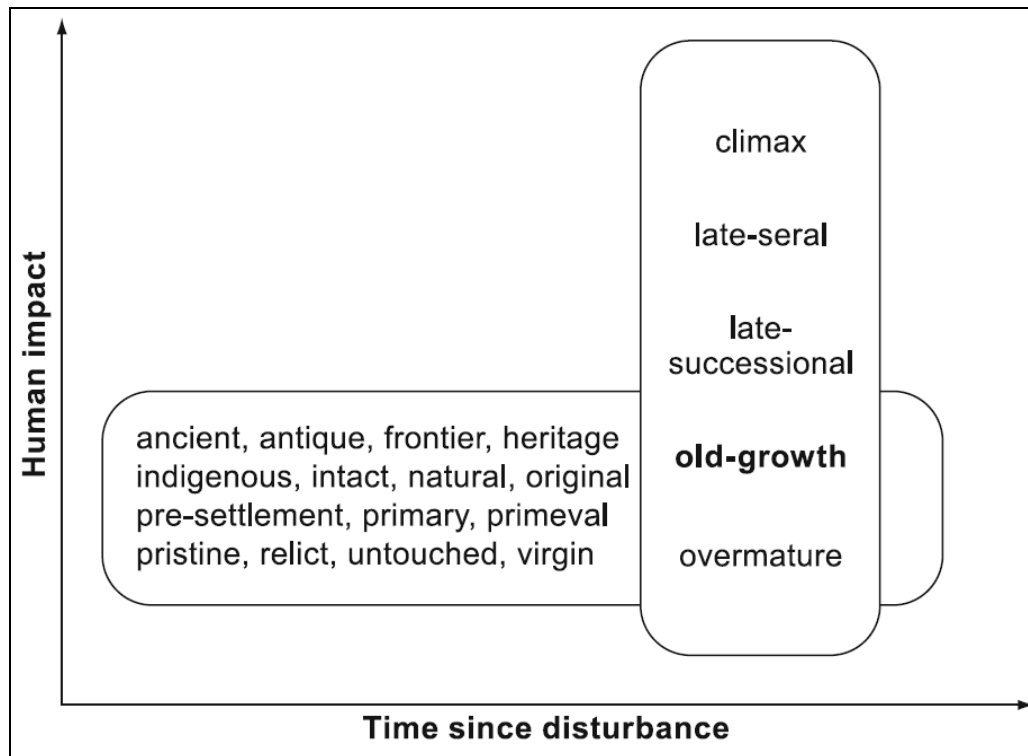


Figure 3.2: Commonly used terms in place of ‘old-growth.’ Terms are arranged as a function of time since disturbance and human impacts. The majority (horizontal box) designate stands with a low degree of human impact. The terms in the vertical box denote stands that have not been disturbed for a long time (Wirth et al. 2009).

Of the three indicator groups used to determine the status of forests as old growth, the forest structural characteristics are the easiest to determine. Structural characteristics are the distribution of different sizes of trees, which is largely dependent on age. First and foremost—tree ages are either uneven, multimodal, or inverse J-shaped in distribution. Unlike the present forest age distribution in Figure 2.10 which is bell-shaped, tree age distribution should have multiple high points and be uneven. This translates into a complex multi-layered canopy structure. These forests exhibit large amounts of dead wood, either standing or downed, in all states of decay. The final characteristics relate to age—the majority of trees will reach half their

maximum age, while some of them will approach it (Wirth et al, 2009). Forest structure will have multilevel canopies and diverse tree ages in an old-growth forest.

Old-growth stands, successional defined, are composed entirely of trees that developed in the absence of external processes, namely pioneer species which dominate a region after it has been clear-cut. Successional features are the development stage at which forest are at. Figure 3.3 illustrates this principle. The full old-growth stage may be delayed if pioneer species, which are the first to enter a system after disturbance, are long lived, as their presence crowds out other, late successional species (Wirth et al, 2009).

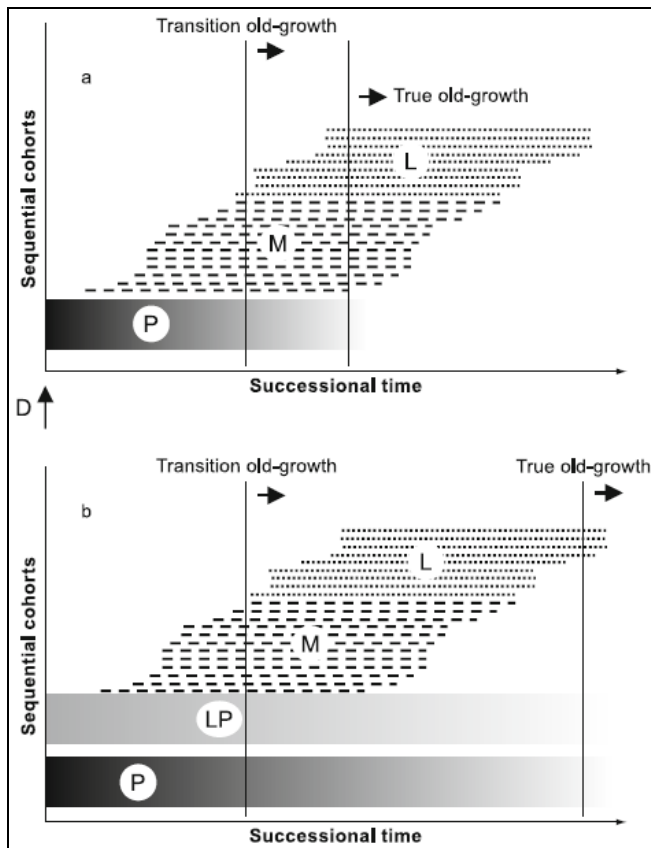


Figure 3.3: This image (Wirth et al. 2009) illustrates successional criteria of old-growth. In scenario a), a site is colonized by pioneers (p), and then shifts to mid-successional (m) and eventually late-successional (l) species. Scenario b) demonstrates that true old-growth conditions are reached much later if long-lived pioneers (lp) are present. The onset of the transition to old-

growth stage is not affected, but under the successional definition the forest does not become true old growth until all pioneers are gone.

The final method of characterizing old growth, biogeochemical features, is the most difficult to measure. Biogeochemical features are the rate at which forest processes occur. Old growth forests exhibit closed nutrient cycles, reduced tree net primary production, zero net accumulation of biomass, and increased understory generation (Wirth et al. 2009). In essence, these characteristics indicate that the forest is done growing and developing, as such it is stable: inputs equal outputs. Determining values such as understory generation and primary production takes much labor and time and is fiscally intensive, as such biogeochemical features are rarely used to determine a forest's maturity.

These classification systems focus upon various features, but collectively they quantify an old-growth forest as the following: A varied forest that is at the height of its development, containing largely older trees, but also consisting of younger woods, which together produce a system that can sustain itself at a high level of diversity, is stable, and capable of persisting in the long term. The age at which forests achieve old-growth characteristics varies. On average it can be as little as 150 years for boreal conifer forests and as high as 500 years for tropical broad-leaf evergreens. In the case of temperate forests, such as those of Pennsylvania, old-growth forests range from 200-400 years in age and are around 325 years old on average (Wirth et al, 2009).

Time is the key element that gives old growth forests their qualities—diversely aged forests of mixed composition that are at the peak of their biological capacity. Gas development affects forest systems in ways that affect each of the three old-growth indicators 1) Structural—building drilling pads in forested areas and eventually replanting them will lower the average forest age in the vicinity of the pad. 2) Successional—by clearing an area, drilling pads are reintroducing pioneer species to forests; these species may take a significant amount of time to

disappear. 3) Biogeochemical—gas development will affect local nutrient cycles through indirect edge influences in the surrounding forest. For these reasons, management of forests must focus on long-term effects of present gas development activities, as they do not only affect the forest's present capabilities, but also those capabilities generations into the future.

Chapter 4: Ecology of disturbances and Landscape Ecology

The goal of my study is to quantify landscape disturbances. A disturbance is “any relatively discrete event in time that disrupts ecosystem, community, or population structure and changes resources, substrate availability, community, or the physical environment” (Pickett & White, 1985). Disturbance can shift a system from equilibrium to non-equilibrium and tip subtle biological balances (Turner, 2005). Disturbances create habitat fragmentation and increased patchiness which lead to localized extinctions (O'Neill, 1997).

Landscape resilience determines whether local species are likely to recover from disturbances. Landscape resilience is the rate at which a landscape recovers from disturbance. Landscape vegetation recovers after a disturbance at a rate determined by landscape resilience, by the nature of the disturbance, e.g. whether the disturbance was natural or anthropogenic, to what degree it occurs, and the biome it is located within. For example, forests will take longer to recover than grasslands because in most cases trees have much slower growth rates than grasses (O'Neill, 1997).

Spatial analysis, while in many ways a young science, is an effective tool in determining the nature of and changes in habitat patches at a landscape scale. When disturbances have a long-

term impact upon ecosystems spatial analysis of disturbances is effective. The data generated by spatial analysis, when paired site-specific data such as species distribution, water quality, etc., can be used effectively to analyze and address landscape scale issues. However, landscape analysis can be subject to bias in the way they are performed, the sheer number of landscape metrics can obscure changes in landscape influences. As such, efforts should be taken to consider these factors when performing landscape analysis.

While landscape analysis is a good tool for assessing the health of an ecosystem, it is only a tool. On-site research characterizing the effects of surface disturbances is necessary to contextualize the data landscape analysis produces. This chapter explores both the science of landscape analysis and how anthropogenic landscape disturbances affect biodiversity. Disturbance results in habitat loss, edge effects, population isolation, barrier effects, road mortality, and increased human access—influences that are best seen in edge effects and habitat fragmentation (Benítez-López et al., 2010).

Edge Influence

The creation of new edges is key in understanding anthropogenic disturbances. In nature, forest edges tend to be highly variable and non-linear in nature, thus softening transitions between biomes. Roads and pipeline construction either flatten this irregular border or create new forest edges (Harper et al., 2005). The creation of edges affects landscapes on many levels, both biotic and abiotic, from the soil to the canopy. Biotic effects are seen in changes in species composition and abundance. Abiotic effects include changes in wind, light, and moisture. These edge influences extend both outward from the edge into the newly created region and into the forest. Edge influences are felt unevenly across species and biomes. They increase habitat

access, material, and energy for some species at the same time as they negatively affect the system's original biodiversity (Harper et al., 2005).

The impact of edge influence varies depending upon how an edge is created and used. Natural edges, which may occur because of fires or windstorms, may not affect ecosystems as negatively as anthropogenic effects, as the ecosystem has adjusted to these periodic disturbances, which are short lived and not maintained (Harper et al., 2005). Of anthropogenic disturbances, highways present the greatest degree of ecosystem disruption. The wider and more highly used a road is, the more of a barrier it presents to species attempting to travel between forest fragments (Harper et al., 2005). However, even narrow roads have marked effects upon ecosystems. So, the nature of disturbances have marked effects upon their biological impacts.

Several other factors may increase the impact of edge influences. Some are specific to the biome, such as homogeneity in ground cover, and canopy height and composition. If a forest naturally contains regular clearings, the negative ecological effects of well pad development are not as negatively felt as they would be if they occurred in completely forested areas. A few influences are historically based, such as the number of pioneer species (higher after previous disturbance), exotic and invasive species, or the soil depth, which may be influenced by human actions (Harper, 2005). Not all disturbances are created equally. Depending upon how they are created and maintained and where they are situated, they will have different impacts upon the ecosystem.

Microclimate is also affected by edge creation. The orientation of the disturbance relative to the sun and prevailing winds can have a marked impact upon the interior. In some cases edges are oriented perpendicular to prevailing winds, which makes edge trees susceptible to wind

throw. Light also plays a role. At higher latitudes, the creation of edges enables light to penetrate deep into the forest and change ecosystem diversity and growth rates. Increased light and wind susceptibility are estimated to directly affect a distance equal to 2 or 3 canopies height into the forest (Harris, 1984).

Ecosystem response to surface disturbance

Forest ecosystems respond in two phases to surface disturbance—primary and secondary—and manifest these responses in both changes in process and structure. The first forest reaction to disturbances is in primary process responses. Process responses are immediate and direct reactions to forest system processes after damage. They include increased evapotranspiration, nutrient cycling, and decomposition. The second portion of primary responses is structural changes, such as canopy and biomass loss, occur as a part of human development, and they continue shortly after the disturbance. The secondary stage of response to surface disturbance is the forest's recovery stage. During this period, process responses, such as increased plant growth, occur. Secondary structural changes include increases in sapling density and growth. The final component of secondary responses is an actual shift in forest composition (Harper, 2005). Figure 4.1 demonstrates these processes.

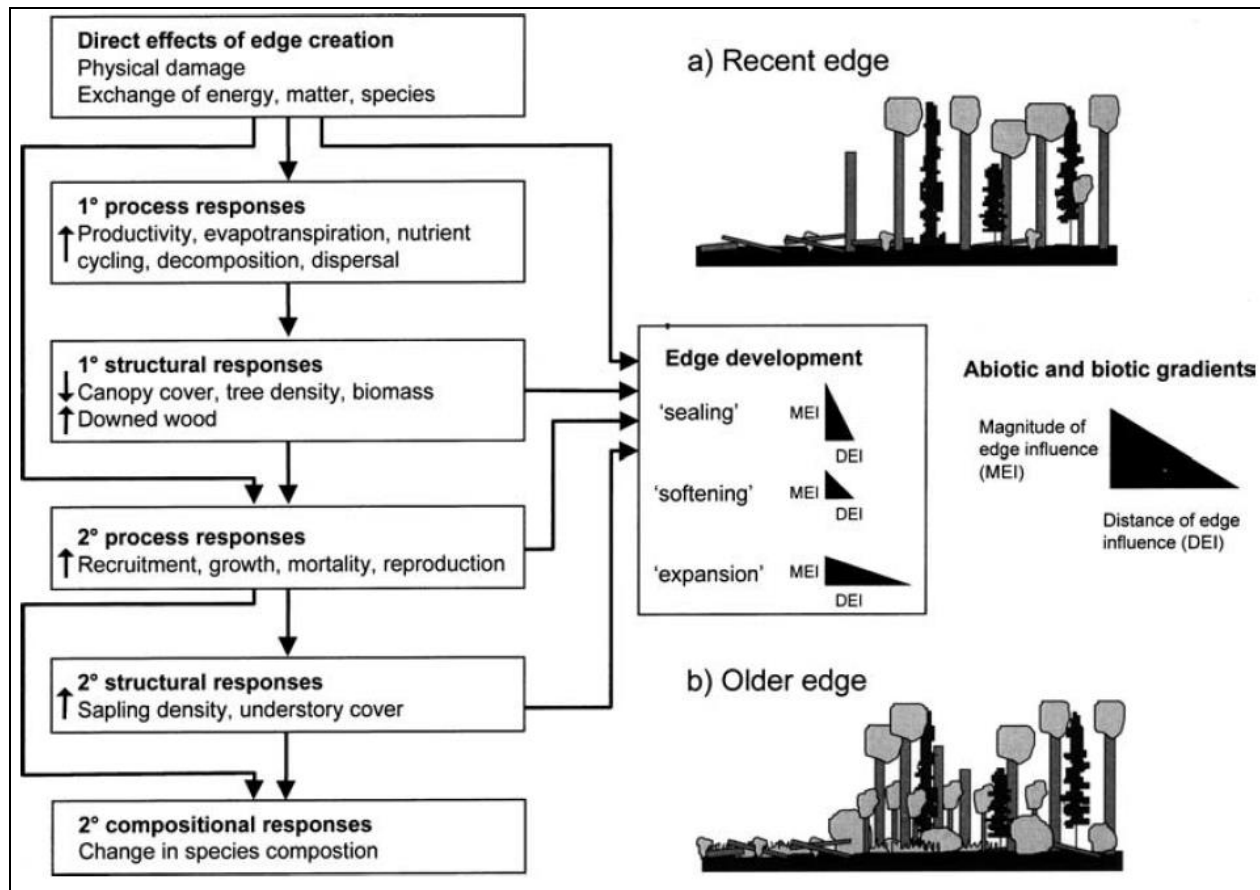


Figure 4.1: Conceptualized diagram explaining primary and secondary responses to edge creation. This diagram demonstrates forest transition from a) Recent edge to b) Older edge, through the processes of sealing, softening, and expansion (Harper et al., 2005).

Edge development, while transitioning from primary to secondary responses, undergoes three changes (Figure 4.1). The first is *sealing*. During this primary period, the magnitude of edge influence (MEI), which is the degree to which the creation of edge affects and changes the forest composition, is at its highest value. However, during the primary response, the distance of edge influence (DEI), which is the distance to which edge influence extends into the forest, is at its lowest point. During the sealing stage, immediately after disturbance, an ecosystem is least fitted to adapt to the pressures of the environment, and as such, it is damaged to a high degree. The next phase of change in edge development is *softening*. During this period, the extreme nature of the MEI decreases, and distance of edge influences (DEI) remains the same. During the

softening phase. MEI approaches equaling DEI; this phase lies between primary and secondary responses. During softening forest cover has begun to adapt to edge creation. The final stage is *expansion*. During this secondary period DEI expands into the forest understory as pioneer species expand out from the edge and into the surrounding forest (Harper, 2005). Edge creation is a complex, multistep process that has lasting effects upon forest ecosystems.

Disturbances, in the form of prior land use, have a lasting effect upon the forest composition. The lasting effects of agriculture are displayed in the following two examples. First, areas of France that were deforested and farmed by the Romans for two centuries still show variation in species richness as a function of former agricultural intensity nearly two millennia later (Dupouey et al, 2002). Similarly, Massachusetts' historical land use has greatly influenced present forest composition. There are distinct differences between current forest composition on formerly farmed vs. virgin lands (Mozkin et al., 1999). Given these considerations, it is likely that disturbance from gas development, even if it is remediated, is likely to have long-term effects upon ecosystems.

Effect upon species

These changes in the physical edge that bring about process and structural changes in forests have pronounced effects, both positive and negative, on many species. The remainder of this chapter aims to elucidate these effects and explore how they are modeled.

The negative effects of disturbance also abound. Linear disturbances from gas development present a number of risks. In short, they increase predation and parasitism, while decreasing the ability of species to migrate (Nekola, 2012). Linear disturbances facilitate

movement, not only of exotic plants and mammals, but poacher's ability to penetrate core forest (Ercelawn, 1999). While facilitating movement, corridors simultaneously act as barriers to species traveling between forest patches. Roads, in particular, increase animal mortality and introduce foreign substances, such as heavy metals and organic compounds, into the environment. Mowing linear disturbances, such as non-road corridors (pipelines), prevents transitional ecosystems from arising and threatens small animals living in these areas (Nekola, 2012). Finally, road creation leads to increased human development (Trombulak & Frissell, 2000).

Birds

The relationship between birds and surface disturbance is well studied. Bird species are separated into three groups in relationship to forests—edge, deep forest and unaffected species. Edge birds thrive near anthropogenic disturbances, deep forest birds only thrive within a distance of edges, and unaffected species are indifferent. One study has shown that there is no change in bird concentrations relative to traffic, suggesting initial disturbance affects species distribution more than subsequent land use. Even low-use or small roads have significant impacts upon bird species. As birds are so well studied, Benítez-López and others (2010) were able to model bird species' distributions as a function of distance from edge (Figure 4.2). Species abundance greatly decreased immediately adjacent to disturbances. Bird species are affected as far as 1 km from forest edges (Benítez-López et al., 2010). Overall, the effect of disturbances upon birds is negative.

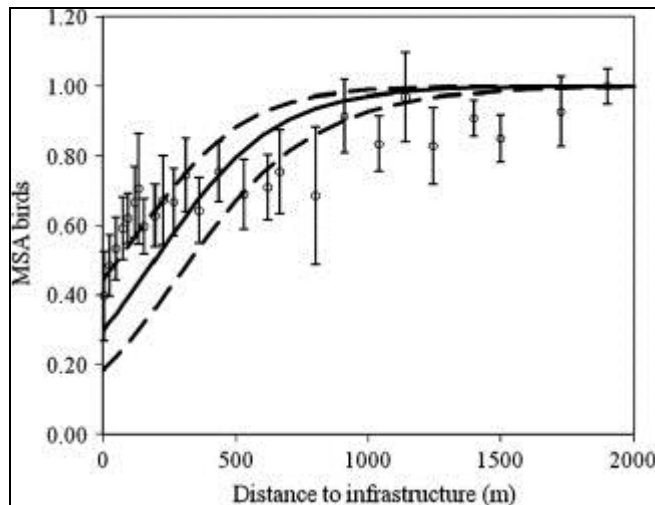


Figure 4.2: Logistic regression between mean species abundance (MSA) and distance from infrastructure. Open dots represent pooled results of several studies. Black line is the estimated curve of MSA decline relative to distance, while dashed lines are the 95% upper and lower confidence intervals (Benítez-López et al., 2010).

Mammals

The second most studied animal class in relation to edges is mammals. The effects of disturbance on mammals can be quite far reaching. Benítez-López and others' (2010) analysis found that mammal populations were affected as far as 5 km from forest edges. Mammals become reluctant to cross roads with margins greater than 20 m, making large roads effective population barriers (Benítez-López et al., 2010). However, even small roads, whether or not they are actively used by humans, are effective barriers for small mammals. Mammal species that have negative impacts upon Pennsylvania's ecosystems, such as deer, are easily introduced to core forest areas along roads and pipelines. Raccoons, skunks, and coyotes, and other nest predators are easily introduced along these paths. Benítez-López and others modeled the effect of infrastructure upon mammals (Figure 4.3, 2010). Their data exhibited a large decline in the original species abundance within 4km of a surface disturbance (Figure 4.3).

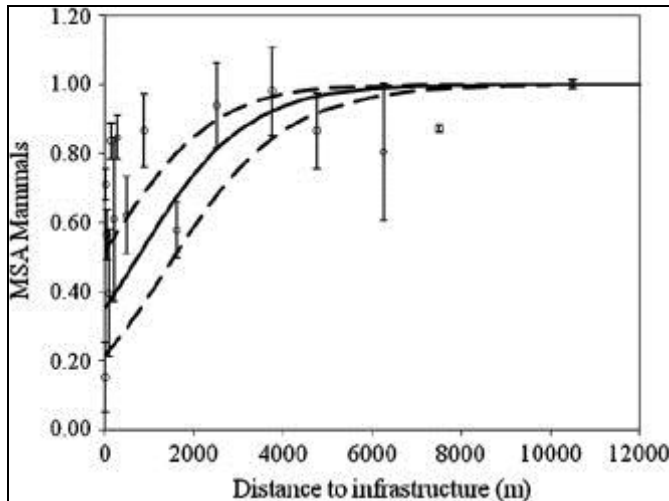


Figure 4.3: Logistic regression between mammal mean species abundance (MSA) and distance from infrastructure. Open dots represent pooled data. Black line is the estimated curve of MSA decline relative to distance, while dashed lines are the 95% upper and lower confidence intervals (Benítez-López et al., 2010).

Among mammals, Whitetail deer present one of the greatest risks to the forest ecosystem. Whitetail deer are a keystone species in Pennsylvania, meaning their actions, specifically their feeding habits, affect many species at many levels of the forest ecosystem (Rawinski, 2008). Whitetail deer have greatly benefitted from forest fragmentation. Prior to European settlement, forests contained relatively sparse deer populations ($<4/\text{km}^2$). Fragmentation has created clearings that provide significant sources of deer forage, and human activities have largely eliminated large predators such as wolves and cougars. This has helped build and maintain today's near-record high deer densities (Alverson et al. 1988; Rawinski, 2008). Deer are highly mobile in fragmented landscapes and easily penetrate deep into old growth forests (Coulon et al. 2004; Alverson et al. 1988). Fragmentation also interrupts large predatory mammals such as black bears, which would regulate deer populations.

Deer populations consume saplings and shrubs. Deer are present to such a great degree in Pennsylvania that they effectively eliminate all native low-growing plants and create ideal

environments for exotic plant species (Rawinski, 2008). In fact, one study found that 98 threatened or endangered plant species were damaged by deer browsing (Miller et al., 1992). This browsing removes young-successional phase growth from forests. Small trees are never given a chance to grow, and this is having devastating and long-term impacts on forests (Rawinski, 2008). Edges, by enabling deer, are further harming forests and reducing their ability to regenerate effectively and transition to mature forest systems.

Other species

The effect of disturbances extends to species other than mammals and birds. For example, sensitive understory plants may be affected by disturbances (Harper et al., 2005) as may be invertebrates. Gastropods are the poorest active distributors in the animal kingdom, meaning that of all species, they are the slowest at distributing their populations. As such, they are useful indicators of distribution rates. Gastropods experienced “profound changes” near disturbances (Nekola, 2012). These profound changes include decreased diversity compared to gastropods in the surrounding forest. However, gastropods in new openings were shown to share similar compositions to gastropods in meadows that were naturally occurring in the area. This further strengthens the observation that naturally heterogeneous landscapes are not as negatively affected by development (Nekola, 2012). Finally, macro-invertebrate soil fauna have also been shown to experience negative influences from edge creation that extend up to 100 m into forests (Haskell, 2000). Figure 4.4 summarizes the magnitude (intensity) and extent (distance) of disturbances for several species groups and other forest indicators. Disturbances likely affect other life forms; however, little research has been performed that reveals these effects.

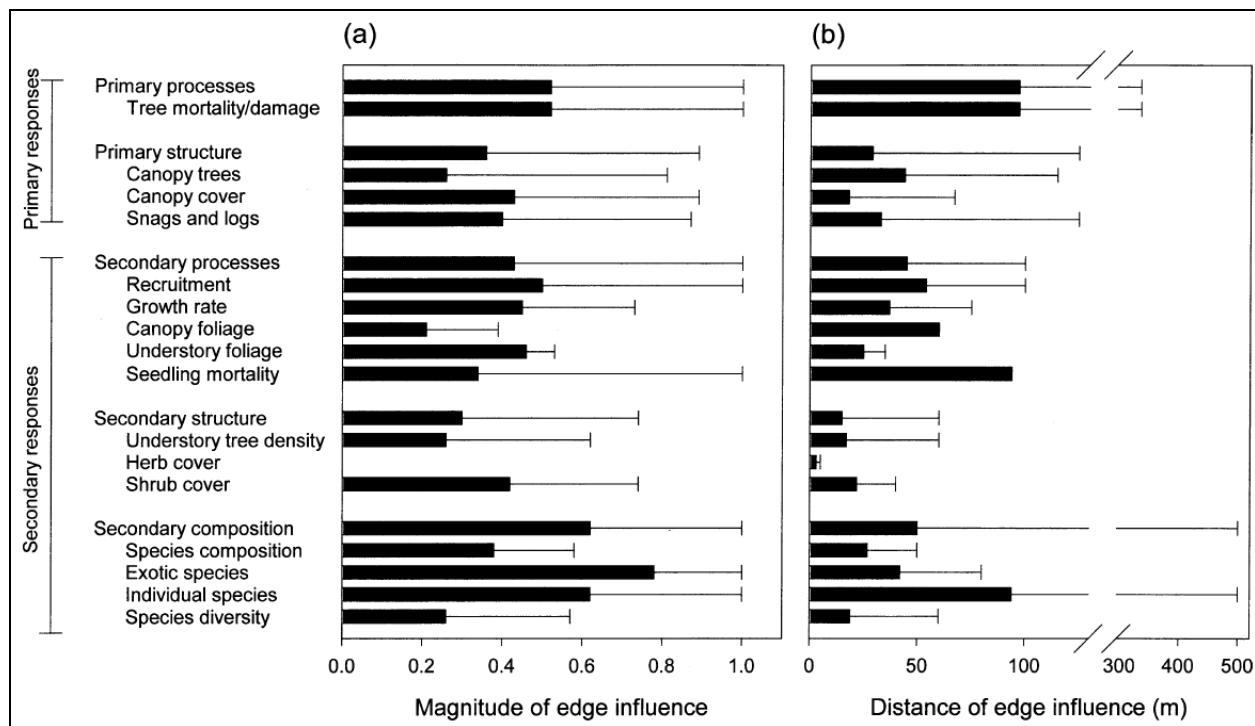


Figure 4.4. The magnitude (a) and extent (b) of edge influence in response to different variables (Harper et al., 2005).

Landscape ecology

My study is based on the emerging science of landscape ecology, a field that has grown rapidly in the past 20 years (Turner, 2005). Landscape ecology focuses on interactions between spatial pattern and ecological processes in different habitat patches. Namely, it enables scientists to characterize the problems of habitat fragmentation and edge influence that have been outlined above. Because of landscape ecology, it is now widely known that fragmenting, or dividing continuous patches of forest into smaller areas, negatively affects species that thrive in forest interiors (Fahrig, 1997). Since its emergence, the field of landscape ecology has experienced dozens of landscape pattern metrics, which are created by analyzing landscapes and determining things such as total edge and habitat size. Metrics measure everything from land use distribution to the nature of forest edges in an attempt to characterize the relationship between landscapes and ecosystem components. The abundance of landscape metrics has been reduced; there are

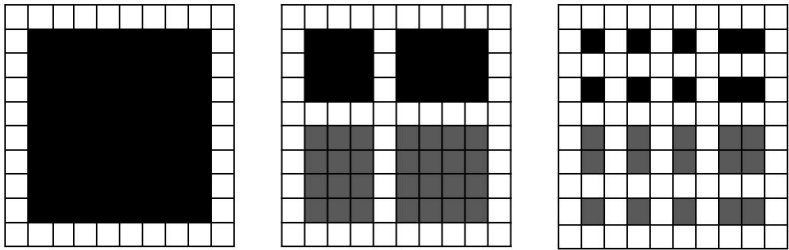
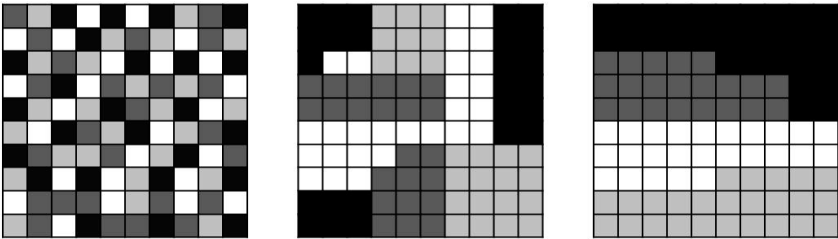
now a few choice metrics that scientists consistently use (Riitters, 1995). While there are many metrics with which to analyze landscapes, disturbance and temporal change remain prominent rubrics in landscape ecology (Turner, 2005).

Landscape analysis can be used at scales large enough to make political decisions upon how to manage natural resources (O'Neill et al, 1997). The hydraulic fracturing moratorium in the Susquehanna River's watershed, forest management in Pennsylvania, and the moratorium on drilling in New York demonstrate the differing local, state, and regional management levels.

Landscape Metrics

Fragmentation statistics, which are the metrics used to measure the nature of landscape habitat composition, are abundant and can easily drown the analyst in information, so clear study objectives are necessary. Riitters and others (1995) analyzed 55 landscape metrics in order to determine the redundancy between statistics, as many of them indicated the same things. They were able to reduce this to a set of 26 metrics, a set of six factors best explained about 87% of landscape variation. These univariate factors are average patch compaction—how densely packed patches are, overall image texture, average patch shape, patch perimeter-area scaling, number of attribute classes, and large-patch density-area scaling. The metrics my study employs are based off a few of these factors and are defined in Table 4.1.

Table 4.1: Landscape Metrics		
Term	Definition	Description
Interior Forest	Area of forest at least 100 meters from the forest edge.	The size and distribution of forest patches. (Harper et al, 2005). Graphical representation of patch size and fragmentation A) not fragmented, B) moderate, C) highly fragmented, little to no interior forest.

		 <p>(A) (B) (C)</p>
Forest Edge	Linear measure of amount of edges between forest and other land use in a given area.	When edges expand into ecosystems, the ecosystem can be affected some distance in from the edge (Skole and Tucker, 1993). Forest edge is simply a linear measure of the amount of edges between forest and other land uses in a given area, especially between natural and human-dominated landscapes. The influence of the two bordering communities on each other is known as the edge effect.
Contagion	The degrees to which adjacent pixel pairs can be found in the landscape.	<p>This is an important measure of how landscapes are fragmented by patches. A higher contagion value indicates a less fragmented landscape and more homogenous landscape (McGarigal et al, 2002). Graphical representation of contagion: A) low contagion-close to 0, B) moderate, C) high-approached 100.</p>  <p>(A) (B) (C)</p>
Fractal Dimension (index)	The complexity of patches or edges within a landscape. Generally measure of perimeter to area proportion.	Human landscapes, e.g. fields, tend to have low-complexity shapes, natural cover has complex edges and a higher value. The fractal-dimension index ranges between 1 and 2, with 1 indicating high human influences in the landscape and 2 with natural patterns and low human influence (McGarigal and others, 2002).

Conclusion

In conclusion, landscape disturbance manifests itself at a large number of scales over extended periods. By creating edges that act as corridors and barriers to species, disturbances can have largely negative effects upon not only forest biodiversity, but also upon future forest composition. Landscape ecology is an effective way to address this issue as it created the data

and language through which to understand the cumulative effects of these many small changes upon the landscape as a whole, and as such on entire biological systems.

Chapter 5: Methods

This study's methods utilize mainly publically available GIS datasets and software and are based off of those of Slonecker and others (2012). The overarching goal here was to explore how the extraction of Marcellus shale gas is affecting state forestry systems, especially old growth forestry systems by quantifying the total extent of gas-related disturbance through fragmentation software. In order to do this the project involved four main stages: 1) Site selection, 2) Data collection, 3) Data formatting, 4) Analysis, and 5) Interpretation.

Site Selection Process

To select a study site, I first explored the extent of known old-growth forest fragments in Pennsylvania, which are listed and exhibited in Table 5.1 and Figure 5.1. All of these areas are protected and exist in State Parks, Wild, or Natural areas. Each of these three designations has unique rules that apply to it, and drilling is strictly forbidden on each of them. However, forests adjacent to these sites may not have similar protections. This study focuses on forests adjacent to existing old growth as they are potential sites of future old growth, and areas into which the biodiversity contained in old growth forests may easily spread. According to Davis' estimation, there are presently 3,787 hectares of old growth forest on public land in Pennsylvania (1996). Figure 6.1, displays the spatial location of these old-growth areas in relation to all of Pennsylvania's forests and the Marcellus Shale. There are two key locations where the shale, forests, and old growth regions exist in conjunction. The first contains six old growth sites that are already protected, as the majority of woods there are part of Allegheny National Forest. The

second area is a wide section of continuous forested area in north-central Pennsylvania known as the High Allegheny Plateau. This is the most highly forested region in the state (Slonecker et al., 2012). This region contains three old growth locations and several wilderness and wild areas. I focused on this area as it is the least protected large continuous forest swath containing multiple old-growth sites.

Table 5.1: Location and site of identified old growth forests (Davis, 1996; Dunwiddie et al., 1996).		
Area	Hectares	Old-growth forest type
Cook Forest State Park	610	Eastern White Pine, Eastern Hemlock, Northern Red Oak, White Oak, Black Cherry, Red Maple, Sugar Maple, American Beech, White Ash, Yellow Birch, Black Birch, Cucumber Magnolia
Bear Meadows Natural Area	130	Black Spruce, Balsam Fir bog
Detweiler Run Natural Area	75	Eastern White Pine, Eastern Hemlock
Thickhead Mountain Wild Area	20	Chestnut Oak
Woodbourne Forest and Wildlife Preserve	49	Eastern Hemlock, Sweet Birch, Sugar Maple, Northern Red Oak, White Ash, American Beech
Holtwood Environmental Preserve	81	Chestnut Oak, Eastern Hemlock, Umbrella Magnolia
Anders Run Natural Area	20	Eastern White Pine, Eastern Hemlock, Cucumber Magnolia, American Beech, American Hornbeam, Black Cherry, Oak
Sweet Root Natural Area	26	Eastern Hemlock, Sweet Birch, Eastern White Pine, American Basswood, White Oak, Red Oak
Hearts Content Recreation Area	49	Eastern White Pine, Eastern Hemlock, American Beech
Tionesta Scenic and Research Natural Areas	1600	Eastern Hemlock, American Beech, Sugar Maple[3]
Allegheny Islands Wilderness	63	Silver Maple, Sugar Maple, American Sycamore, Slippery Elm
Bark Cabin Natural Area	30	Eastern Hemlock, Northern Red Oak, White Ash, Bigtooth Aspen, Hickories
Johnson Run Natural Area	11	Eastern Hemlock, Eastern White Pine
Forrest H. Duttlinger Natural Area	64	Eastern Hemlock, American Beech, Black Cherry, Sugar Maple
Snyder Middleswarth	100	Eastern Hemlock, Eastern White Pine, Pitch Pine

Natural Area		
Hemlocks Natural Area	49	Eastern Hemlock
Ricketts Glen State Park	810	Northern Hardwood Forest
Total	3787	

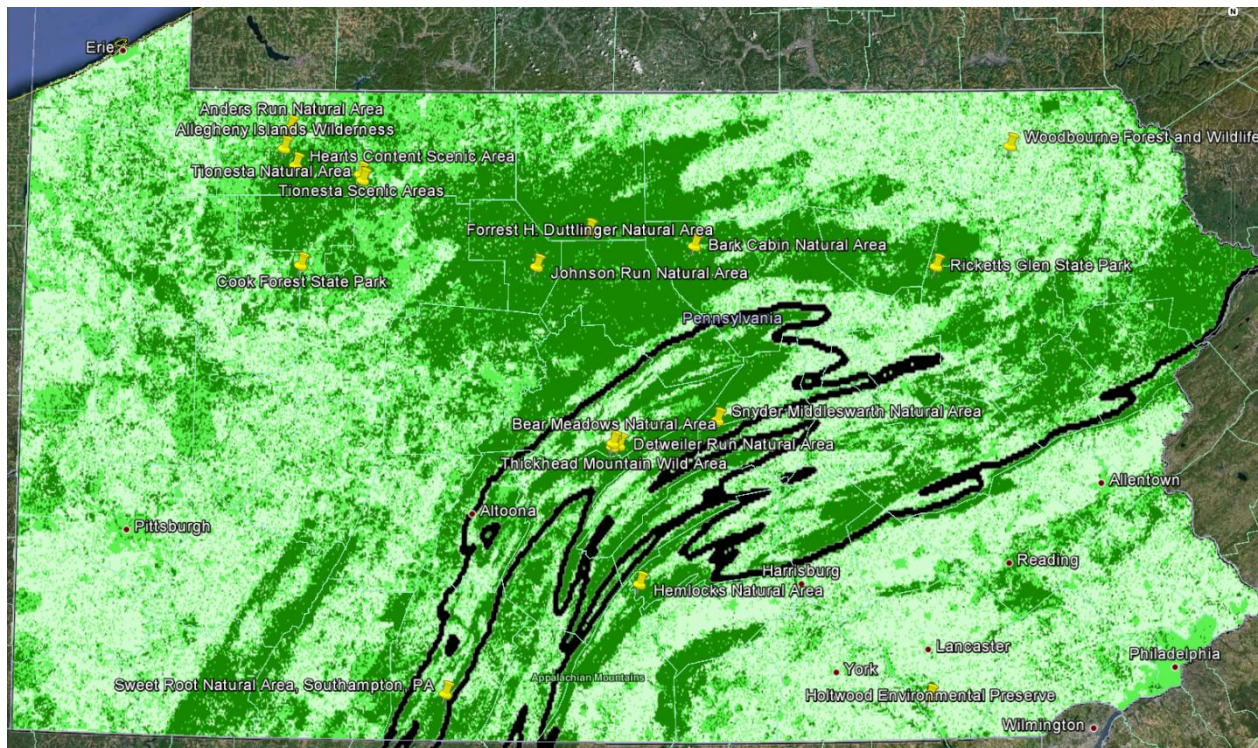


Figure 5.1: Location of identified old growth forests (placemarks) along with current forest cover data. The bold black line marks the extent of the Marcellus shale, which lies above and to the left of the bold black line (Davis, 1996; Dunwiddie et al., 1996; Petroski 2013)

The high Appalachian plateau region is also central to Jenkins and others' (2004) quarter-million hectare old-growth forest system (Figure 5.2). By using additional data from well permits and drilling projections, I selected one county in which to begin my analysis. In order to best characterize the extent of Marcellus wells, I used well permit and gas projection data (Figure 5.3) to determine which areas within the highly forested high Appalachian plateau were most likely to see the greatest amount of continued surface disturbance (Johnson et al., 2010). Pennsylvania state data are generally available by county; I approached this project on a county-by-county

basis. Taking the factors outlined above into consideration, this study began analysis with Clinton County (Figure 5.4). Over 80% of Clinton County is currently forested, and present well permit data and projections indicate that there are and will be a large number of gas wells drilled in the County. The following counties, also in the High Allegheny Plateau, were also examined: Cameron, Centre, Clearfield, Clinton, Elk, Lycoming, Potter, and Tioga. Figure 5.5 outlines the location of these counties in relation to Pennsylvania state forest and current areas under lease as well as areas with severed mineral rights where development is likely to occur. Areas with severed rights have separate owners of the mineral rights; owners of mineral rights can disturb the surface to access the gas. Figure 5.6 outlines the designated study area in pink; this contains the hydrologic units (HU8), which are groupings of different levels of watersheds, that intersect Clinton County. A subset of this area was studied for forest fragmentation— Moshannon, Sproul, and Tiadaghton state forests.

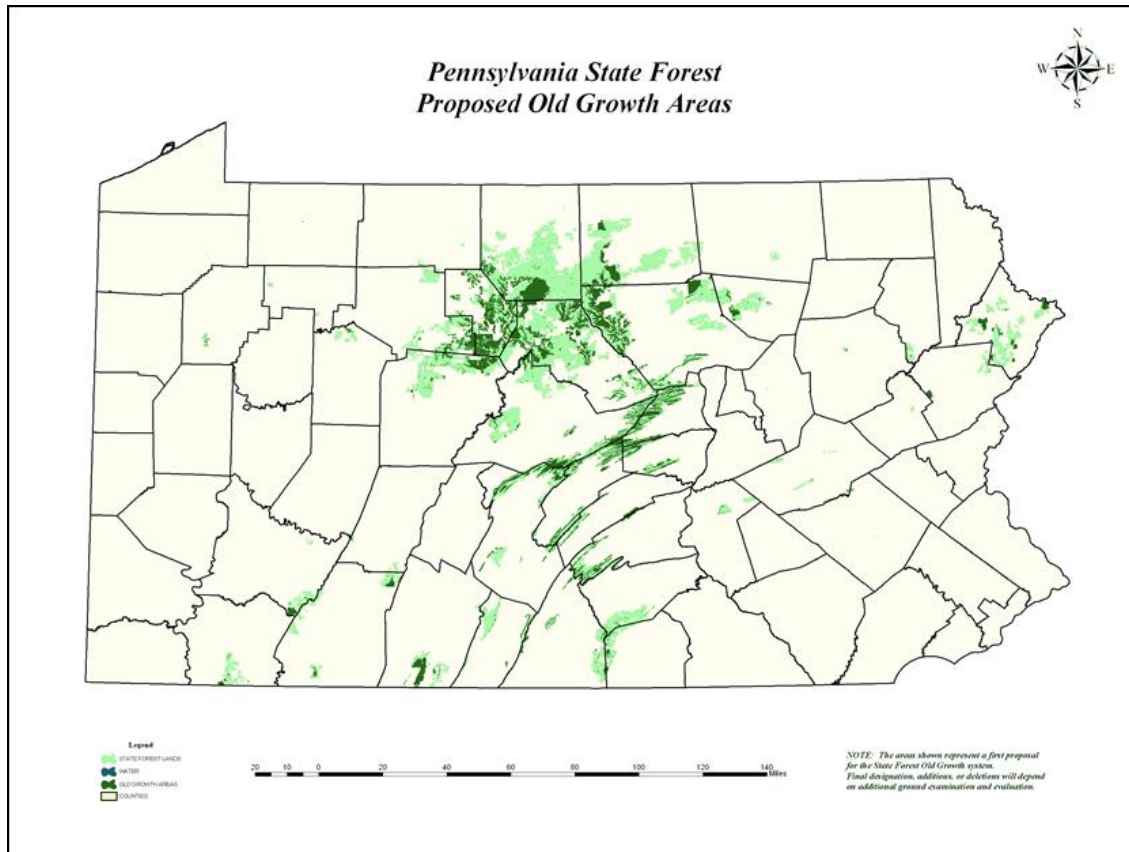


Figure 5.2: Proposed half-million acre old growth forest system outlined in dark green (Grace, 2003).

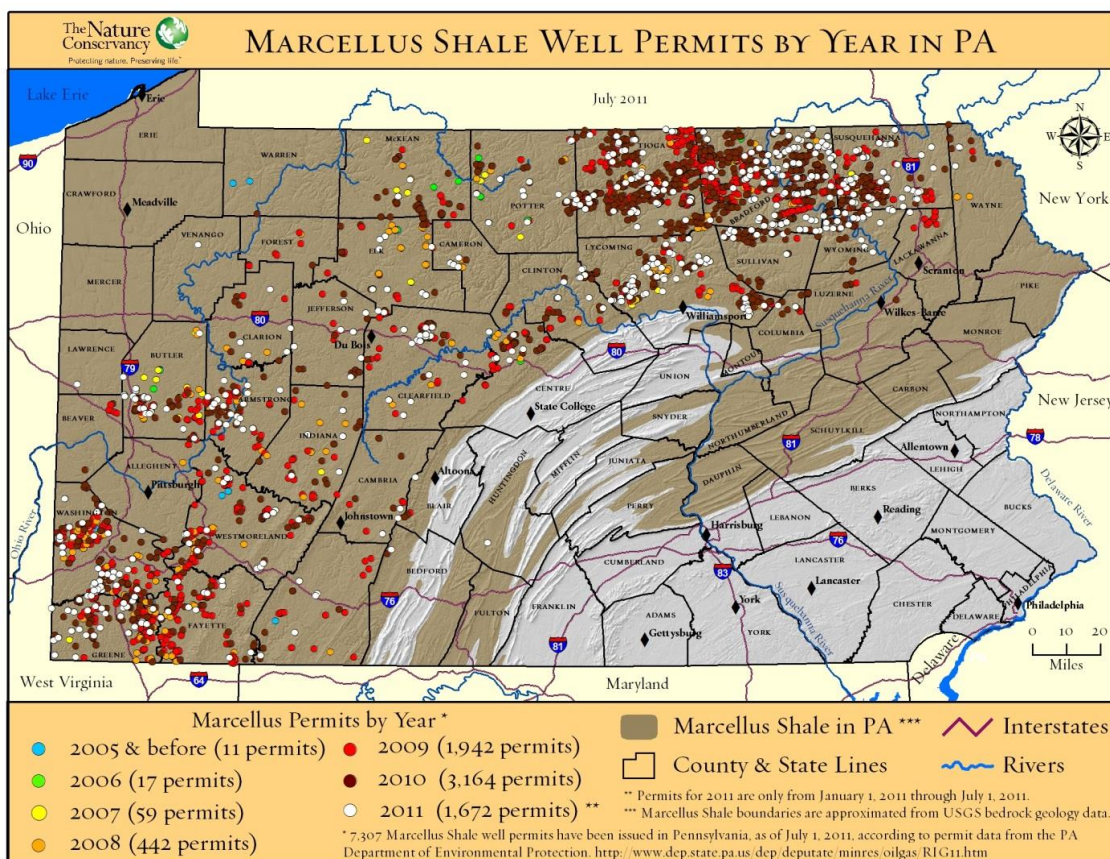


Figure 5.3: Map of the Marcellus shale well permits by year in Pennsylvania (Johnson, 2010). Note that few permits prior to 2008 exist in Cameron, Centre, Clearfield, Clinton, Elk, Lycoming, Potter, and Tioga Counties, the proposed study area.

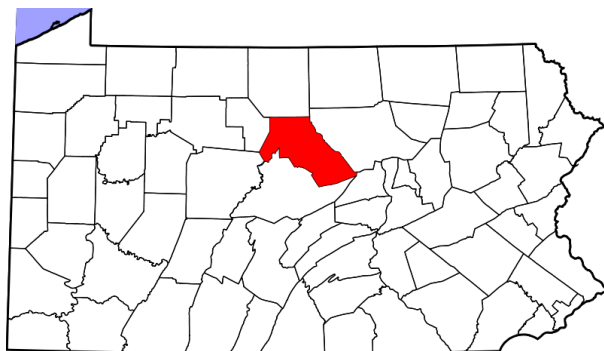


Figure 5.4: The location of Clinton county (Source: https://familysearch.org/learn/wiki/en/images/2/20/Clinton_County_PA_Map.png)

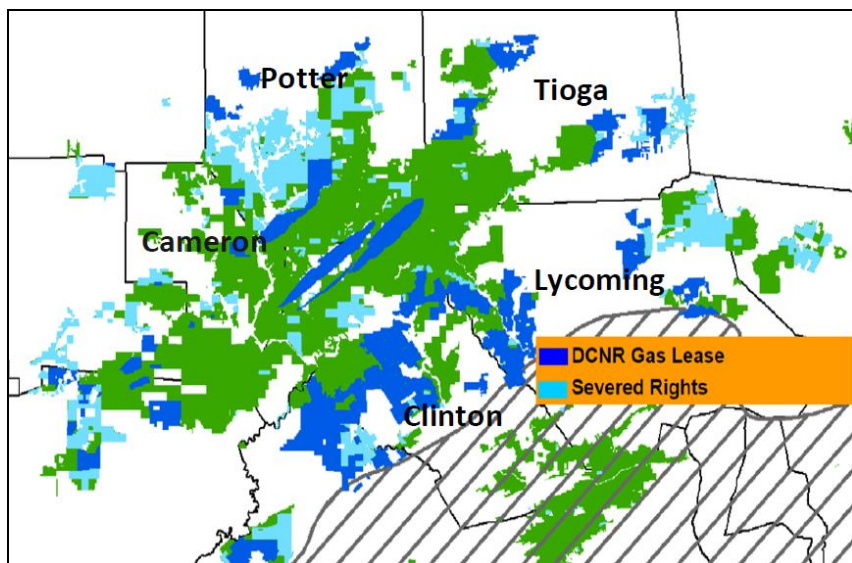


Figure 5.5: The locations of Clinton, Lycoming, Tioga, Potter, and Cameron counties relative to state forest land and the present leased gas areas and areas of severed rights (PA DCNR, 2012)

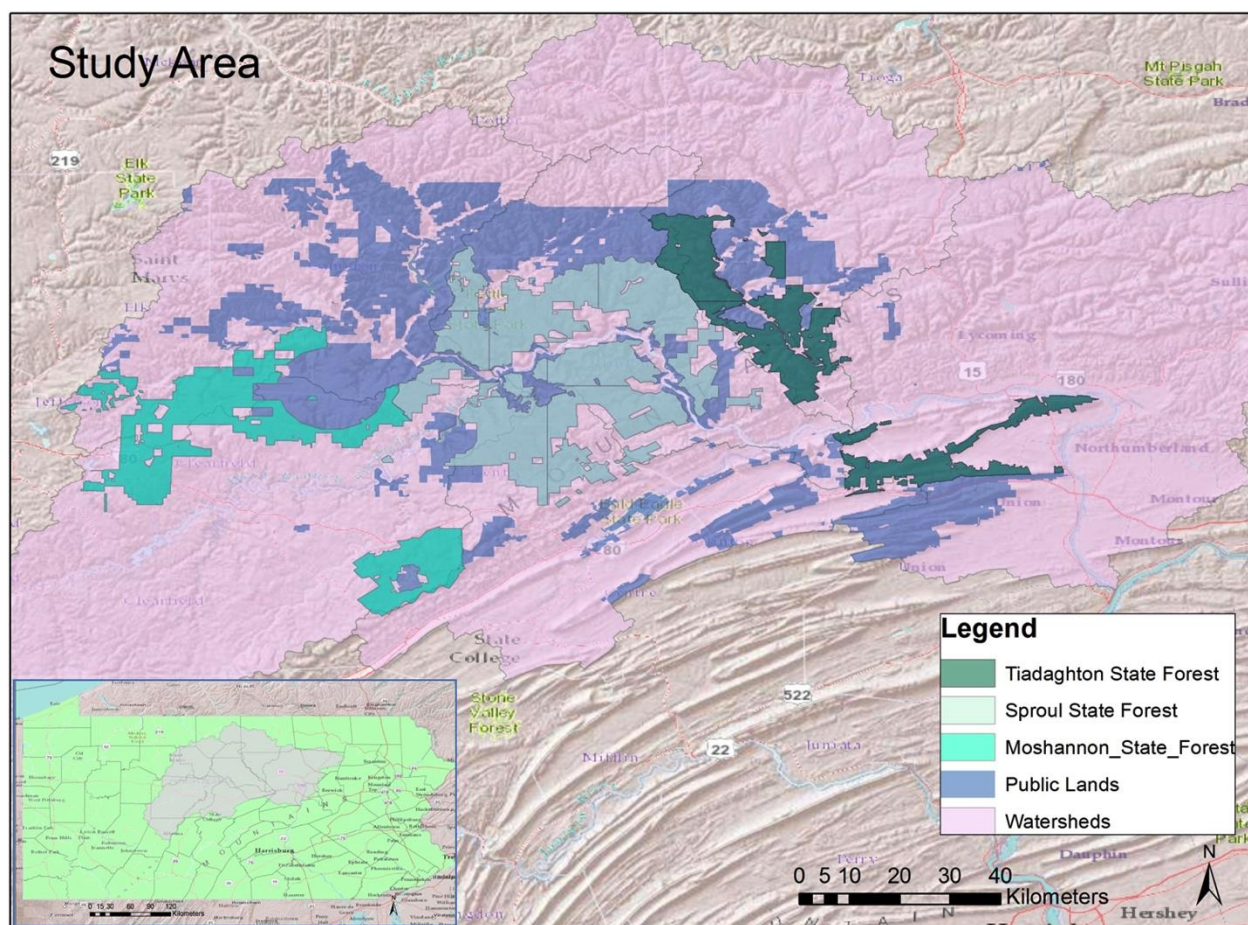


Figure 5.6: Study area—HU8 hydrologic units that intersect with Clinton County are outlined in pink. Studied State Forests include Moshannon, Sproul, and Tiadaghton state forests.

Data Collection

Data used for this study came from publically available resources from the private and public domains:

- The Pennsylvania Spatial Data Access (PASDA) site was used to obtain county specific data.
- Well data were digitized using high-resolution aerial images (1-meter resolution) from the National Agricultural Imagery Program (NAIP). Using Google Earth, imagery from the years 2005, 2008, and 2010 was utilized (USDA, Farm Service Agency, 2011).
- Additional visual data confirming surface disturbance at later dates than 2010 were obtained using high-resolution Google Earth imagery from October 30, 2012.
- The Carnegie Museum of Natural History Pennsylvania Unconventional Natural Gas Wells Geodatabase was used to determine well sites. This database was created using well permit data, which contains current and proposed well locations. These locations were located on Google Earth. Sites that showed development were digitized as polygons and their roads and pipelines were digitized into polylines (Carnegie, 2013).
- These data, once processed, were incorporated into the National Land Cover Database (NCLD) for the Conterminous United States from the year 2006 (Horner et al., 2007; Fry et al., 2011). The NCLD is a 27-class land cover classification system covering the conterminous United States at 30-meter spatial resolution (Table 5.2). Table 6.2 outlines how these were reclassified and simplified for this study. Land class cover divisions were generally grouped in order to maintain a focus on forestland.

Table 5.2: NCLD Land Class Cover Divisions (Fry et al. 2011)	
Original Land Class (n=27)	Reclassification for this study (n=4)
Open water	Surface Water
Perennial Ice/Snow	Surface Water
Developed, Open Space	Developed Land
Developed, Low Intensity	Developed Land
Developed, Medium Intensity	Developed Land
Developed, High Intensity	Developed Land
Barren Land	Developed Land
Unconsolidated Shore 1	Scrub
Deciduous Forest	Forest
Evergreen Forest	Forest
Mixed Forest	Forest
Dwarf Scrub 2	Scrub
Scrub/Shrub	Scrub

Grassland/Herbaceous	Scrub
Sedge Herbaceous 2	Scrub
Lichens 2	Scrub
Moss 2	Scrub
Pasture/Hay	Developed Land
Cultivated Crops	Developed Land
Woody Wetlands	Scrub
Palustrine Forested Wetland 1	Scrub
Palustrine Scrub/Shrub 1	Scrub
Estuarine Forested Wetlands 1	Scrub
Estuarine Scrub/Shrub 1	Scrub
Emergent Herbaceous Wetland	Scrub
Palustrine Emergent Wetland (Persistent) 1	Scrub
Palustrine Emergent Wetland 1	Scrub

- Marcellus Shale assessment unit boundaries were acquired from the USGS Energy Resources Program Data Services Web Site (USGS, 2012).
- USGS Watershed Boundary Dataset Hydrologic Unit Codes were acquired from the USGS National Hydrography Dataset Website (USGS, 2012),

Formatting

This study's workflow process for data processing before FRAGSTATS is outlined in Table 5.3. This process is adapted from Slonecker and others' (2012) work. The main goal of the data formatting step was to create an updated ground cover map of 2006 NLCD data that would incorporate natural gas disturbance as another dataset.

Table 5.3: Formatting steps	
Step	Description
Format Base NCLD layer	
1	Data Collection (see section above)
2	Clip 2006 NCLD layer by hydrologic unit (HU8) watershed boundaries (Figure 1; USGS, 2012) covering or partially touching Clinton County (the core of the forest regions in Pennsylvania). This includes 8 counties: Cameron, Centre, Clearfield, Clinton, Elk, Lycoming, Potter, and Tioga. Incorporate roads layer by rasterizing it and then using mosaic to superimpose it onto the NCLD
3	Reclass NCLD layers to classes outlined in Table 5.2. (Roads classed as developed land)
4	Clip NCLD layers separately from Moshannon, Tiadaghton, and Sproul State Parks, (they

	are too big collectively to process in FRAGSTATS)
5	Export File as an Image, process in FRAGSTATS.
Processing pad, road, and pipeline data	
6	Export well permit sites in KML to Google Earth
7	Digitize pads (polygon), pipelines and roads (polyline) in the outlined watershed area
8	Export polygon and polyline data to ArcMAP
9	Determine average polyline length, and polygon size.
10	Buffer line by 10 meters on each side (20 total)
11	Convert buffered polyline to raster
12	Convert polygon to raster
13	Using mosaic, overlay polygon and buffered polyline rasters into NCLD layer from step 3
14	Reclassify raster so that gas development is grouped with developed land (Table 5.2).
15	Repeat Steps 4-5

The Carnegie well permit sites were used with spatial imagery to compare the sites before and after drilling. Digitized disturbance data were created in two separate spatial layers: well pads, roads and pipelines. Well pads were characterized as cleared areas relating to existing permits. Only roads created as transportation corridors expressly for shale development were utilized. In addition, only new pipelines leading away from sites and connecting to the larger system were utilized. Other features, such as compressor stations, processing plants, and storage tanks, were also considered. Disturbances from wells and other sources such as pads for trucks were saved as polygons. Roads and pipelines were saved as one vector (polyline) layer, each buffered by 10m on each side, the typical width of forest clearing associated with these features.

The disturbance polygons and lines were combined and converted into raster format, which was then used to update features from the 2006 NLCD. County shape files were merged and internal boundaries dissolved to create the county disturbance footprint. The rasterized disturbance footprint was used to reclassify pixels of the 2006 NLCD and create a new class—gas extraction disturbance—as is exhibited in Figure 5.7. Disturbance polygons and lines were

also quantified by class to determine the total disturbance and the average amount of disturbance per well. These data were quantified such that they could be compared to other studies.

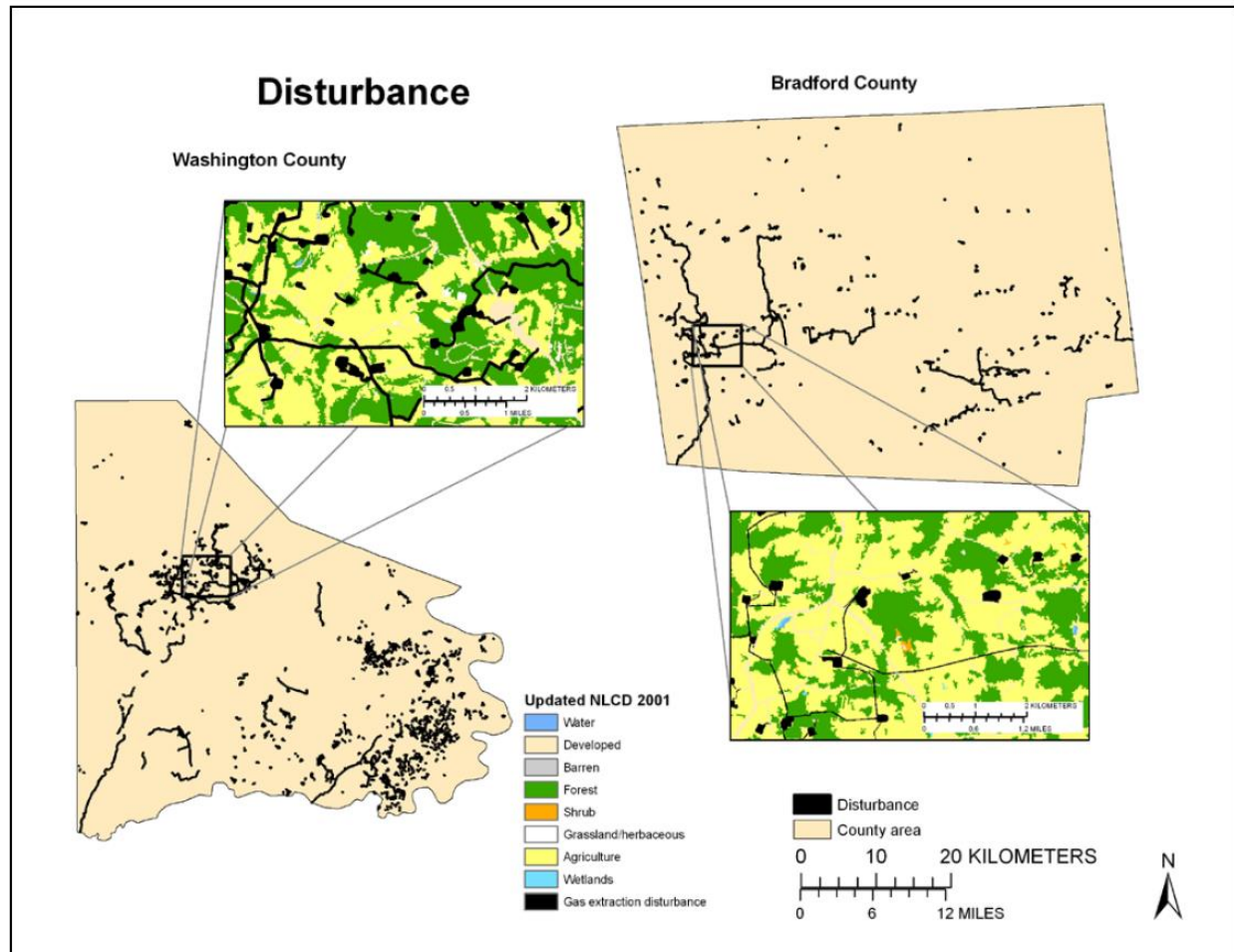


Figure 5.7: An illustration from Slonecker et al.'s study (2012) of created gas extraction layers and their incorporation into a land use classes.

Analysis

Landscape analysis was first performed on the unaltered 2006 NLCD raster to establish a baseline. Analysis was then performed with the updated disturbance NLCD raster. Landscape analysis was performed using two programs. FRAGSTATS was used to create land-cover fragmentation statistics (McGarigal et al., 2002). ATtILA was used to create land-cover class-detailed statistics, forest fragmentation statistics, and forest condition (interior, edge, etc.).

(Ebert & Wade, 2004). These landscape metrics represent those outlined by O'Neill and others (1997). Results are outlined in the following chapter.

Chapter 6: Results

Statistics obtained from the landscape analysis as well as disturbance data are charted and mapped for further analysis, as is seen in the following tables and figure. Table 6.1 outlines the surface disturbance values for gas infrastructure and describes both the linear and total areas of disturbance. On average, 3.4 hectares are disturbed per well pad, including roughly one half of a kilometer of road and pipeline. Table 6.2 outlines the differences between gas developments on private vs. public property. Pads on publically owned land are smaller in size than pads on private land patches due to stricter environmental regulations and enforcement, and leases with tighter limitations in terms of land-use rights.

Table 6.1: Surface disturbance from Marcellus Shale (MS) gas infrastructure on the study area					
MS Land Cover Disturbance	Count	Footprint disturbed (hectares)	Road/pipeline (kilometers)	Disturbed hectares per site	Road/pipelines kilometers per site
MS pads	274	647.8	-	2.35	-
MS roads/pipelines	165	176.1	85.8	1.067	0.518
All MS infrastructure	439	823.9	85.8	3.417	0.518

Table 6.2: Average Road and Pad Disturbance (Hectares)	
All pads and roads	3.42
Pads on public forest land	3.14
% Difference	8.59

Table 6.3 outlines changes in the NLCD land cover classification before and after the analysis. Only developed land cover increases noticeably. Other land cover types either stay the

same (water), or decrease. Table 6.4 outlines landscape metrics from both before and after gas development. Total edge increases slightly. The mean fractal index, contagion, and percent forest decrease slightly. The number of patches increases by almost 2.7%, while the mean core forest decreases by 2.8%.

Table 6.3: The land cover before and after disturbance figures were factored into the analysis. Percent land cover presented in descending order.			
Land cover	Original land cover with infrastructure	Updated with MS sites and roads	Percent Change
Forest	94.17	94.12	-0.0531
Developed	3.619	3.667	1.326333
Water	0.02453	0.02453	-0
Scrub	2.1901	2.182	-0.36985

Table 6.4: Landscape metrics determined from FRAGSTATS			
Land cover	Original land cover	Updated with Marcellus infrastructure	% change
Total area (hectares)	2479528	2479528	0
Total edge (km)	10,005.17	10,047.37	0.42178
Mean fractal index	1.2944	1.2924	-0.1545
Contagion	87.685	87.626	-0.067
Number of patches	4340	4456	2.672
Forest mean core or interior forest area (hectares)	1445.868	1405.581	-2.7864
Percent Forest	94.16587	94.1241	-0.0444

Chapter 7: Discussion

My results correspond to those of several other studies, namely those of Drohan et al. (2012), Johnson et al. (2010), and Slonecker et al. (2012). My study's disturbance of 3.4 hectares per pad is the same order of magnitude of Johnson (2010), who found a disturbance of 5.7 hectares per well pad on public and private Pennsylvanian land. Differences between these values may be due to difficulty in determining the location of pipelines; the large majority were not discernible at the scale of this study. Wiser land use planning on public land, since the time of Johnson's study (2010), because this is a more ecologically sensitive region, could also contribute to this reduction.

The reduction in pad disturbance on public vs. private forest land corresponds with Drohan et al.'s (2012) results, which indicated that well pads on public, rather than private land, have fewer hectares of disturbed land from gas development. Public land may show reduced disturbance due to the presence of regulatory bodies and enforcement bodies such as the Pennsylvania DCNR.

Change in forest land cover at a -0.0531% in Figure 6.3 is small, but it is much higher than the value of decrease in forest cover of Bradford county, which only measured -0.001247% (Slonecker et al. 2012). This area had a much higher concentration of wells but, because of the county's urban and suburban nature, these changes in land cover were not as greatly felt.

Table 4.1 assists the interpretation of Table 6.4; data from this table are displayed in Table 7.1 next to data from the more developed Bradford County in Pennsylvania (Slonecker, 1994). Interior forest decreased in this other study. Forest edge increased in Bradford more than it did in my study. The fractal index was very close to 1 in Bradford County; this number became

slightly closer to 1 with gas development. The fractal index in my study saw a greater decrease, approaching 1.3. Fractal index is a measurement of the complexity of patches in the landscape; values closer to 2 are more natural, values that approach 1 indicate high human influences. Contagion is inconsistent. It actually increases in Bradford county, but decreases slightly in my study. This indicates that Bradford became more homogenous because of disturbance, perhaps because of the high amount of disturbance already present in the region, while my study area became less homogenous. Finally, the percent forest decreased in both instances, as would be expected during development.

Table 7.1: FRAGSTATS Landscape metrics Bradford County (Slonecker et al. 2012) vs. my study						
Land cover	Bradford Original land cover	Bradford Updated with Marcellus infrastructure	Bradford % change	This Study original land cover	This study updated with Marcellus infrastructure	This study % change
Total area (hectares)	300,911	300,911	0	2479528	2479528	0
Total edge (km)	26712	26948	0.87576	10,005.17	10,047.37	0.42178
Mean fractal index	1.1068	1.1061	-0.06328	1.2944	1.2924	-0.1545
Contagion	70.7925	71.9771	1.64580	87.685	87.626	-0.067
Percent Forest	56.12	5606	-0.10702	94.16587	94.1241	-0.0444

My data have several shortcomings. Some wellheads appear to be unreported, meaning that either the permit data and well location contained some mistakes, or the imagery was dated. Google Earth simplified viewing forested regions throughout time. However, sometimes imagery was poor quality, and well pads were very difficult to make out. Characterization of roads was also difficult, and if a road existed prior to the study, it was not included unless it was clearly

upgraded. These new road surfaces usually were about 20 meters wide. However, other than these concerns, the data were usually reliable.

Chapter 8: Conclusion

As this study demonstrates through both discussion of prior research into the effects of surface disturbances, and in assessing the fragmentation effects of surface disturbances, surface disturbances negatively influence species now and leave lasting legacies in forest composition. The results outlined in Chapter 7 are only the beginning of what could be 70 years of gas extraction from the Marcellus shale (Johnson et al. 2010). The Marcellus is just the beginning of shale gas development in Pennsylvania. Below it lies the Utica shale, which may begin to be extracted in the near future.

Gas development will set forest remediation plans back by hundreds of years if the proper precautions are not taken. The seemingly small change observed in this study are not small changes in the lives of many of Pennsylvania's 100,000 species. Forests are complex biological machines, even minor damages could have lasting effects. Wise, responsible energy development is needed. Below are four recommendations for ensuring the future wellbeing of Pennsylvania's Forests.

1. Place a moratorium on any future leasing plans in Pennsylvania state forestland.
2. Use funds from existing leases to expand the extent of existing forestland, and to maintain and enhance its structural diversity through silviculture—active management to increase deadwood at forest floors, introducing fences to restrict Whitetail deer movement, etc.

3. Create stricter regulations and increase funding for the Pennsylvania Department of Conservation and Natural Resources. By increasing active management, unnecessary roads and pad development can be avoided, and active pad size can be reduced. Some simple acts, such as using a V-shaped pit for hydraulic fracturing fluid, can drastically reduce the amount of disturbed land (Railroad Commission of Texas, 2013). A V-shaped pit prevents mud from being funneled from the intake to suction point, as such a smaller area is needed to enable rocks transported in the drilling mud to settle out.
4. Appendix A contains some general recommendations on the principles of land use and management. These ecological land use guidelines, as outlined in Figure 8.1, are valuable in creating properly guided land management plans.

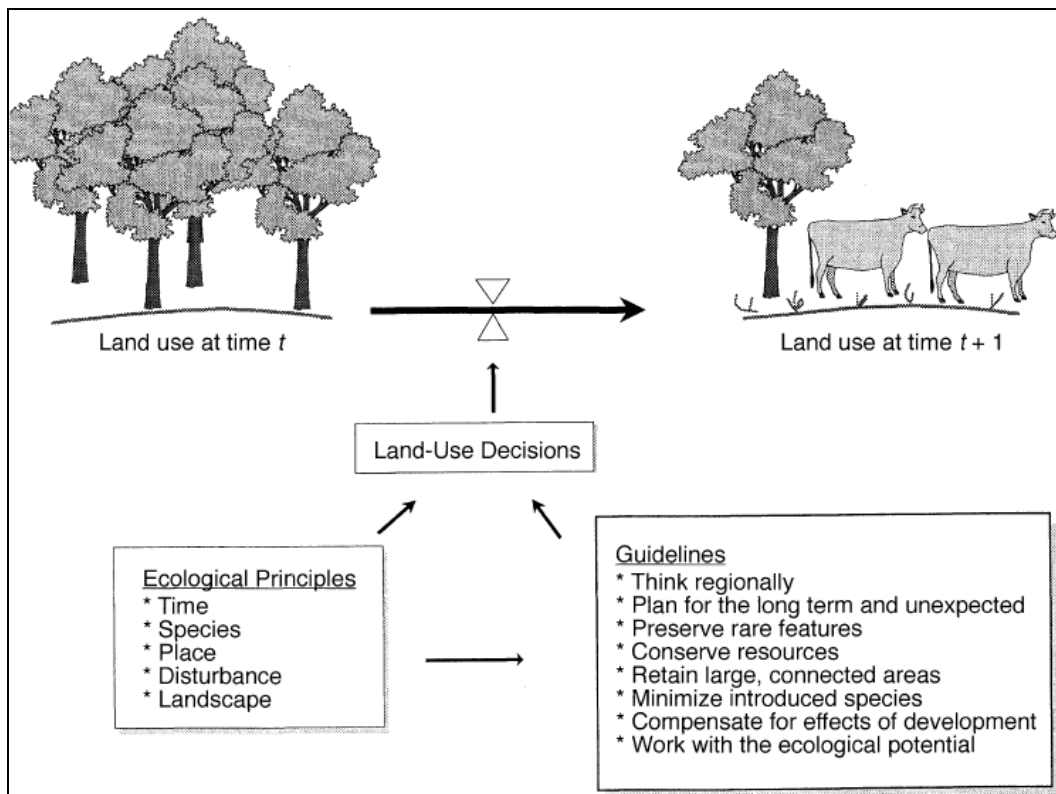


Figure 8.1: Ecological principles relating to land use are developed into guidelines for land managers (Dale et al., 2000).

Future research can expand upon my study in a variety of ways. On the site investigations could explore the degree and nature of gas development effects upon wildlife.

Future research may also employ current data on Pennsylvania critical habitats and explore the degree to which gas development is affecting these critical habitats. Another option would be to use forest patch data to explore how gas development is influencing individual watersheds. My final recommendation is to project the future state of forest fragmentation in 2030. The Nature Conservancy (Johnson et al, 2010) has created three projections (high, medium, and low) of well pad development in 2030 (Figure 8.2). Pennsylvania's forest have a long and rich history. If proper precautions are taken now, then perhaps this rich history will be able to continue on its trajectory and further enrich this state's biodiversity.

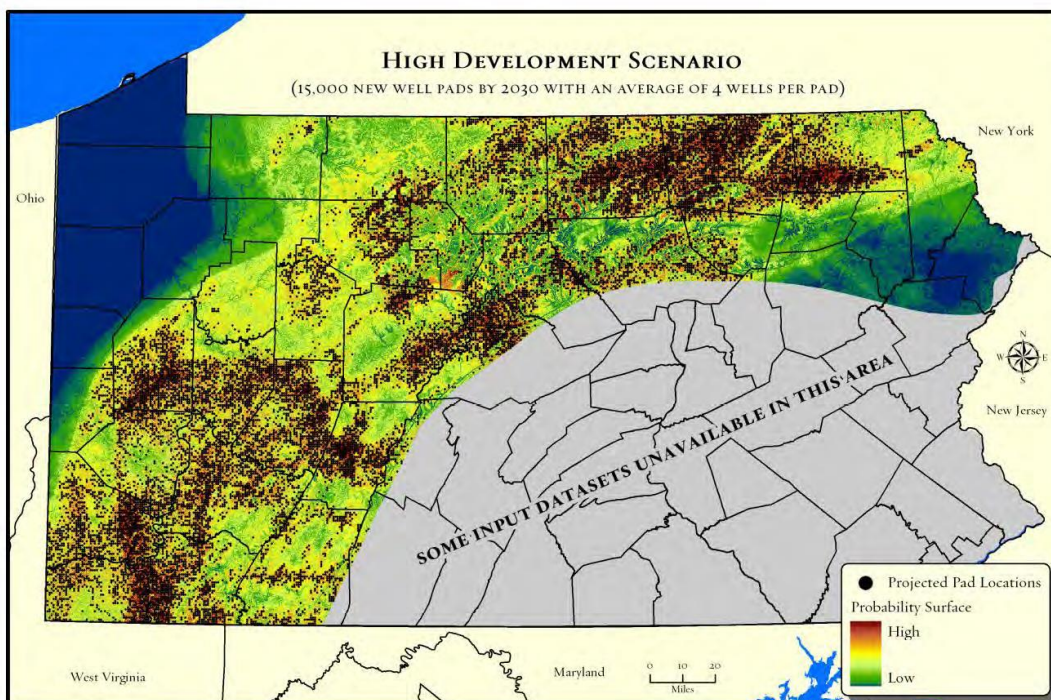


Figure 8.2: A high development scenario of Marcellus Shale well pad distribution for 2030. Projection made using a composite of 50 geospatial data layers; high probability sites contain ideal conditions for gas development, such as topography, formation thickness, etc. Low probability areas do not contain sufficiently thick shale deposits to be economical at this time (Johnson et al. 2010).

Appendix A: Principles of land use, regulations, and recommendations

The future state of Pennsylvania's forests is largely unknown. The answer to that question will depend upon how questions of forest management in a developing gas landscape are addressed. The Ecological Society of America has established five guiding principles to ecological land management involving time, species, place, disturbance, and landscape (Dale et al, 2000). Figure 8.1 demonstrates how these principles and guidelines can be used to make wise land-use decisions.

Various dimensions of the five ecological principles illustrate and inform responsible and sustainable land use decisions. For example, the time principle focuses upon the fact that ecological processes function at many timescales, both long- and short-term. These functions and the paces at which they operate can change through time, and human activities can influence their rates of operation. Forest succession is one example of this principle. After disturbance, early successional plants begin growing, but forests recover slowly and take centuries to recover their form. Similarly, the example of Pennsylvania's forests demonstrates that present forest composition, structure, and function are direct results of past events. The impacts that humans are making today upon forests may not be seen or fully felt until many decades after the initial disruption. As such, knowledge of how forests have been affected by human disturbance in the past, and over what time spans they recover, is essential to responsible land use (Dale et al, 2000).

The second ecological principle guiding wise land use decisions focuses upon species. Forest ecosystems are complex webs of life. As such, anthropogenic activity may influence their components in unexpected and unintended ways. Changes in one species or in networks of species can have broad-scale ecosystem level effects. Table A1 outlines key species classes and how changes to these species can influence a wide range of ecological processes. When any of these species groups show a sign of disturbance or poor health, their decline signifies that there may be room for nonnative species to enter into the system, assume the roles of the natives, and produce marked effects upon the system's biology. This may result in a depleted, low-diversity system that is likely to experience large fluctuations in productivity as weather and resources vary (Dale et al., 2000).

Table A1: Key species classes and their effects (Dale et al., 2000).	
Term	Definition
Indicator species	Their condition is indicative of a larger functional group of species.
Keystone species	Greater effect on process than could be predicted. Affects species through processes such as competition, mutualism, dispersal, pollination, and disease and by modifying habitat and abiotic factors.
Ecological engineers	Alter the habitat and the fates and opportunities of other species
Umbrella species	Have large habitats and thus overlap with many other species' habitat.
Link species	Play critical roles in the transfer of matter and energy across trophic levels or provide critical links for energy transfer.

The ESA's third guiding principle is that of place. Ecosystems are localized to place and processes depending upon a number of factors such as local climate, hydrology, soils, and geomorphology. These conditions will also influence the ability of ecosystems to recover and restore themselves after disturbance. For example, soil composition, once changed, can have lasting impacts on a systems' ecological make-up (Dale et al., 2000).

The fourth principle, disturbance, directly relates to this project. Disturbance events disrupt ecological systems and vary in influence depending on intensity, duration, frequency, and timing. They have the effect of either enhancing or limiting biological succession. Disturbances have important implications for land-use policy (Dale et al., 2000).

The final principle to ecosystem management is that of landscape. The size, shape, and spatial relationships of land cover types influence the dynamics of populations, communities, and ecosystems. These directly influence species' abilities to thrive and move between forest areas. Large decreases in patch size, or increased distances in space can greatly reduce or eliminate the population of some organisms. Fragmentation negatively affects species in numerous ways, and humans often fragment and alter existing landscapes.

Legal justification for forest protection

The manner in which and the extent of human caused fragmentation is based in the government's land management decisions. The government gains legal validation for acting to preserve and regulate practices in forests through three traditional responsibilities: 1) Reducing harm and nuisances, 2) Ensuring orderly timing of development and associated services, and most importantly 3) Protecting public values (Callies, 1994). The role of externalities is a possible basis for public regulation of activities taking place on private lands. The role of the government in land-use decisions is to encourage positive externalities that enhance the welfare of society and to discourage those who harm it. The forest regulatory system is large, intricate, and multi-layered, as is exhibited by Table A2. As such, it often fails to account for and maintain adequate environmental health in the long term (Dale et al. 2000).

Table A2: Different administrative layers of regulatory powers controlling land use Dale et al., 2000).			
Powers	Federal	State	Local
Direct Regulatory			
	Clean Water Act	State endangered-species acts	Land-use zoning
	Endangered Species Act	Growth-management statutes	Agricultural land-use regulations
	National Flood Insurance Program	Regulation and permitting	Storm water management
	Surface mining reclamation	Programs	
	Wetlands/Waterways Reclamation Act		
Indirect Regulatory			
	Tax policy	Property-tax exemptions	Property-tax rates
	Clean Air Act	Transportation policy	Water-use ordinances
	Transportation funding	Economic-development programs	Local services placement and development
	Agriculture programs		
	Subsidies		
Management of publically owned lands			
	Land-use planning	State parks and forests	Municipal parks and recreation areas
	National Wilderness Act	State roads and rights of way	County roads and rights of way
	Wild and Scenic Rivers Act	Regulation of mining and reclamation activities	Green-space systems
	Siting and design of roads and other facilities.		Greenways

Recommendations Guiding Land Use

In addition to the ESA's five guiding principles, the organization has also formulated eight key recommendations for ecological land use, which, if used, will reduce the ecological effects of land disturbance. The first recommendation urges land managers to examine impacts of local decisions in a regional context. This includes identifying the surrounding region and exploring how it is likely to be affected by projects and how adjoining jurisdictions are using and managing their lands. Regional data inventories include: land-cover classes, soils, patterns of water movement, historical disturbance regimes, and the habitat of species of concern. The

process of examining the regional impacts of local decisions also involves establishing system objectives so land managers can act to reach these goals (Dale et al, 2000).

The second recommendation urges planning for long-term changes and unexpected events. Delayed impacts of human land use changes, such as the introduction of invasive species, may not be observed for years or decades after the initial disturbance of a system. Future land use options are constrained by today's and yesterday's decisions. Long term planning must account for the fact that the future may not follow the past and that there are unknowns (climate change).

The third recommendation urges that rare landscape elements and associated species be preserved. The fourth suggests that managers avoid land uses that will deplete natural resources. This includes the prevention of rapid or gradual diminishment of natural resources. The fifth recommendation is that critical habitats in large contiguous or connected areas be preserved and not fragmented. These habitats hold a unique set of physical and biological conditions necessary for an abundance of species to survive, and fragmenting that landscape also fragments populations, which may ultimately reduce a species to a series of patches with populations too small to remain sustainable. The sixth recommendation calls for the minimization of invasive species. The seventh requires reclamation of damaging developments. Finally land-use and management practices should be compatible with the area's potential ecological diversity (Dale et al, 2000). When this eighth recommendation is implemented, a site's potential diversity is assessed, in my study's example the potential of creating a high-functioning old-growth forest, and then land-use management decisions are approached so that they do not impair this goal, in

the case of Pennsylvanian forests—only activities that do not fragment the landscape, not gas development, may be permitted.

In the case of Pennsylvania's forest systems, these recommendations may manifest themselves in a number of ways, including managing the protected core zone so that it is as large as possible, surrounding key ecological sites with buffers, ensuring forest systems are as round as possible to minimize edge influences, and ensuring adjacent land uses will not bring negative external influences (Dale et al, 2000). In terms of all of Pennsylvania's forests, the largest challenge to implementing these rules of sustainable landscape is jurisdictional fragmentation. This occurs when, as in Pennsylvania's forests, many part of the same system are managed by different bodies, which impedes wise environmental planning (PA DCNR, 2010).

The recommendation lists above are all focused at land managers, who continue improving their processes through scientific research. Scientific knowledge has greatly improved both local understanding and management of forests in several ways and will continue to do so in the future. Research has revealed ecological interaction between pristine and heavily used areas that merits further exploration. Spatially explicit models that integrate social, political, and ecological land uses will greatly benefit land-use planners. Both remote data and data obtained from on-site enable us to improve our understanding of forest systems and predict the effects of climate change (Dale et al, 2000).

The eight principles are powerful tools through which to guide land use. The negative ecological effects of development activities may be minimized if proper regulatory actions are taken. Land management, when paired with proper scientific data, can be a powerful tool through which to maintain and improve future forest cover.

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